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Title: Comparison of MCNP Variance Reduction Techniques for Linear Accelerators

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Comparison of MCNP Variance Reduction Techniques for Linear Accelerators

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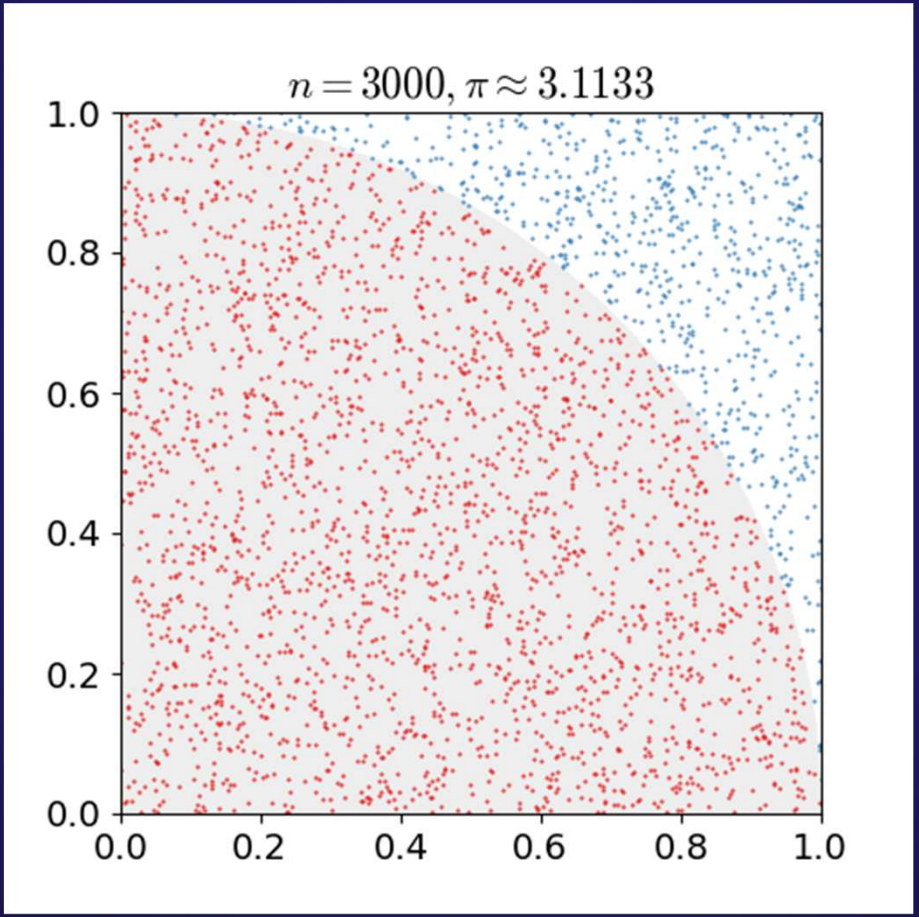
Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

Overview

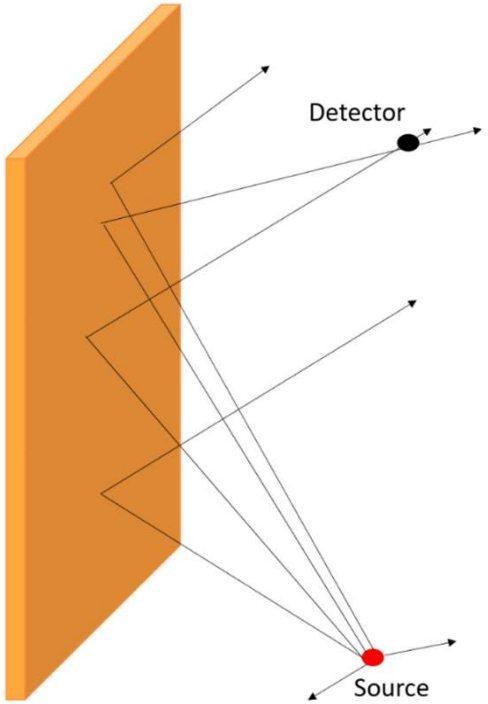
- Monte Carlo Methods
- Accelerators
- This Project
- Variance Reduction Techniques
- Attila4MC

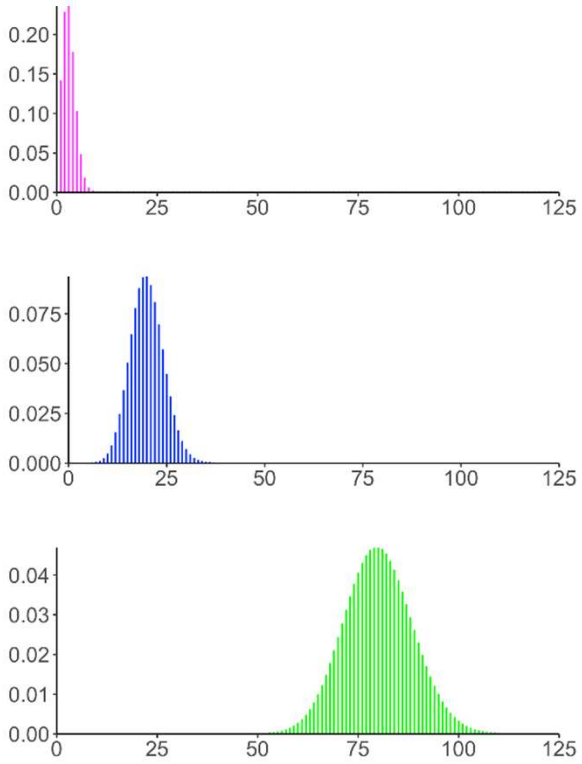
Monte Carlo Methods



Monte Carlo Methods

- Monte Carlo N-Particle (MCNP) transport code
  - Simulates individual particle behavior
    - Through sampling probability densities
  - Records average particle behavior in regions of interest



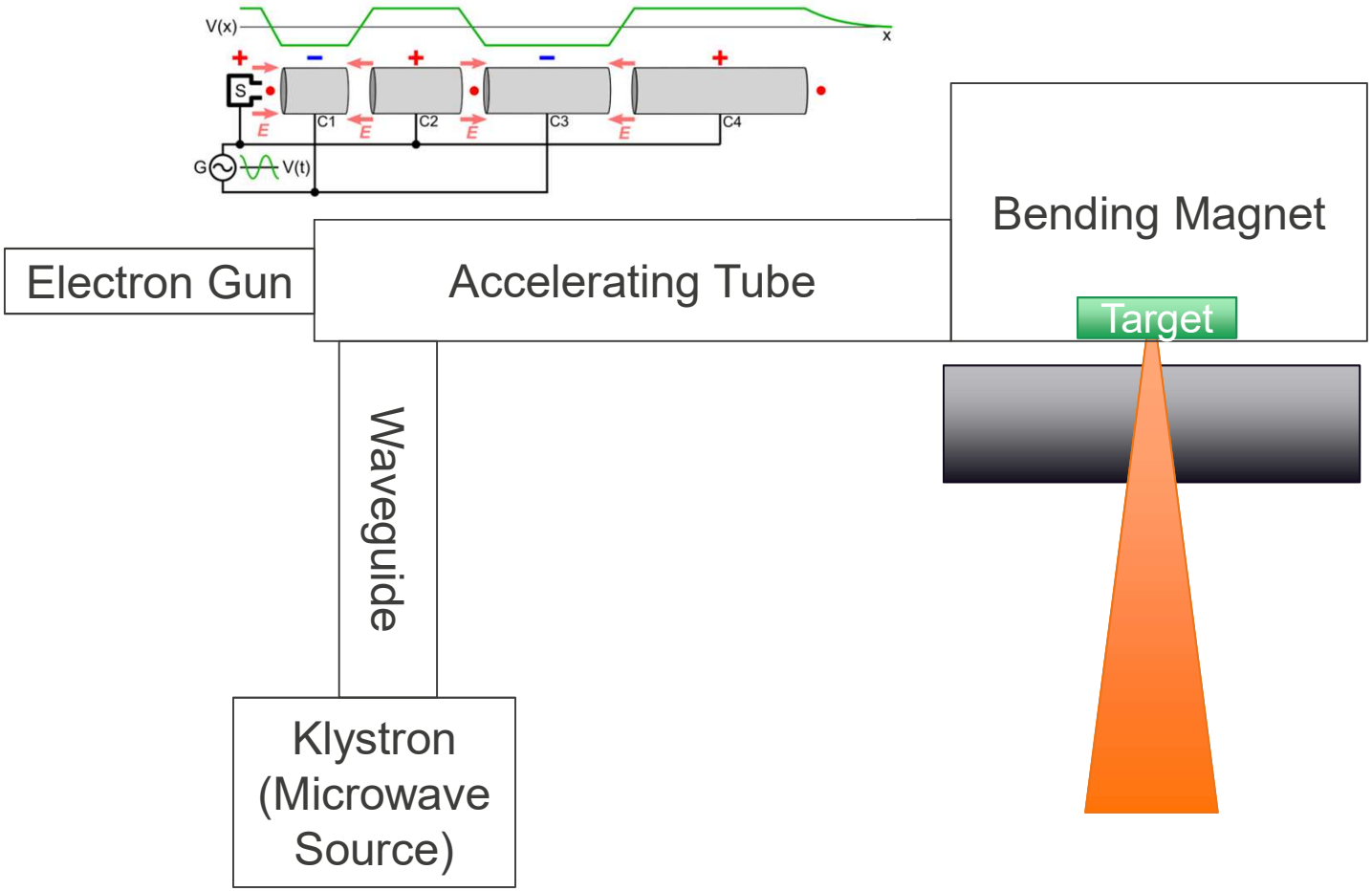


MCNP

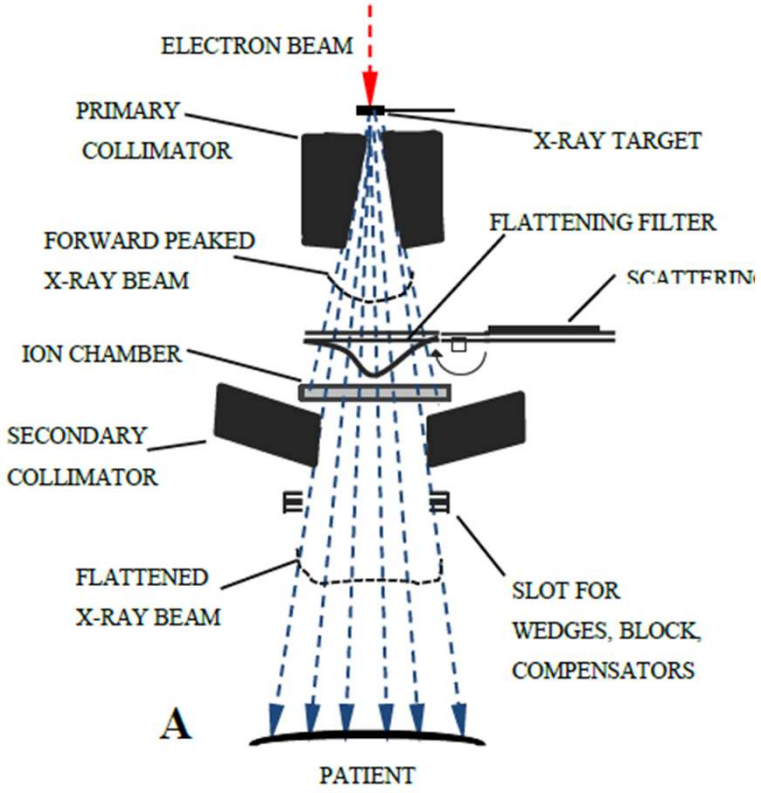
- Shielding and dosimetry modelling routinely performed using MCNP
  - High accuracy, long run times, large times spent on problem definition
  - Availability of a variety of variance reduction techniques to decrease run times
- Utilized extensively in Radiological Engineering
  - Ensuring accuracy of dose calculations very important
  - Reasonable runtimes are important, design is often iterative, requiring many similar runs

Linear Accelerators

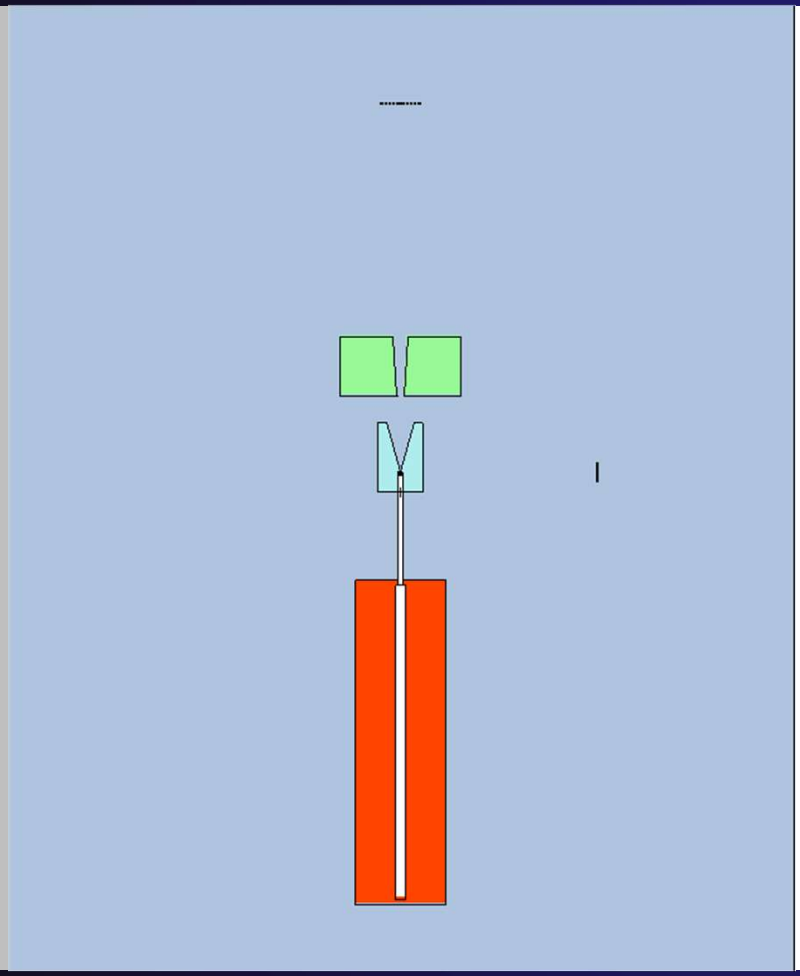
Accelerator Design (Medical)

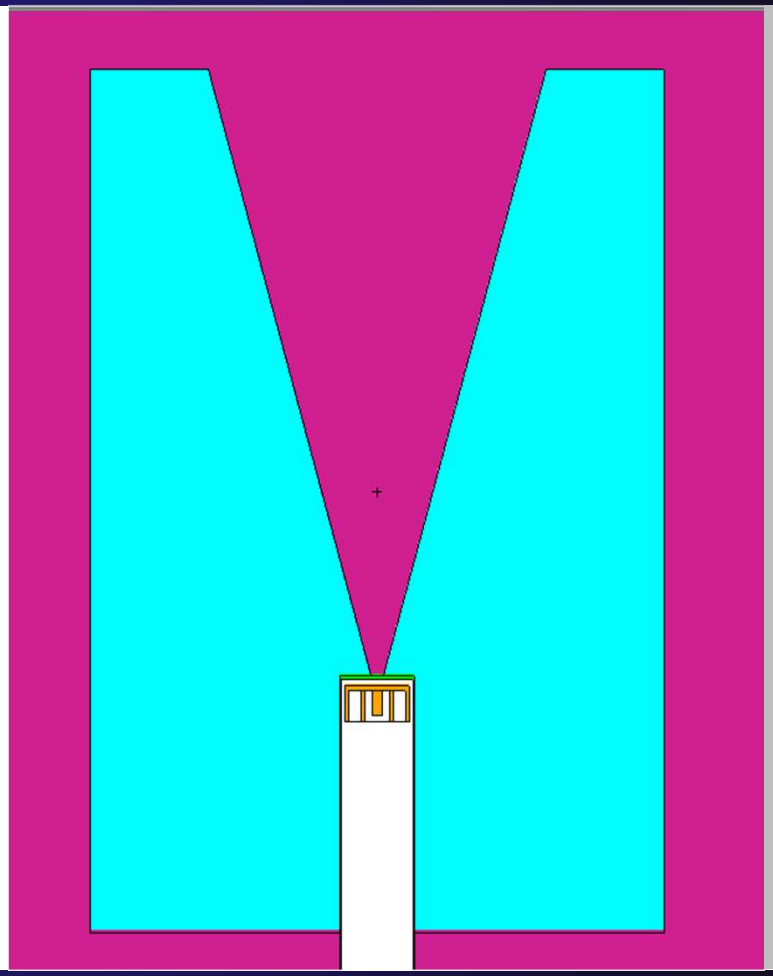


Accelerators



Accelerator Design in MCNP





Efficiency of MCNP Calculations

Variance Reduction

- MCNP run using no variance reduction is often referred to as “Analog” MCNP
  - Sampling distance to collision probability data from an exponential distribution
- Techniques exchange user time for computer time, which may reduce computer time by many orders of magnitude
- Preferentially sampling “important” random walks at the expense of “unimportant” random walks
  - Understanding and defining which random walks are “important” and which are not is the core difficulty with using these techniques

Figure of Merit

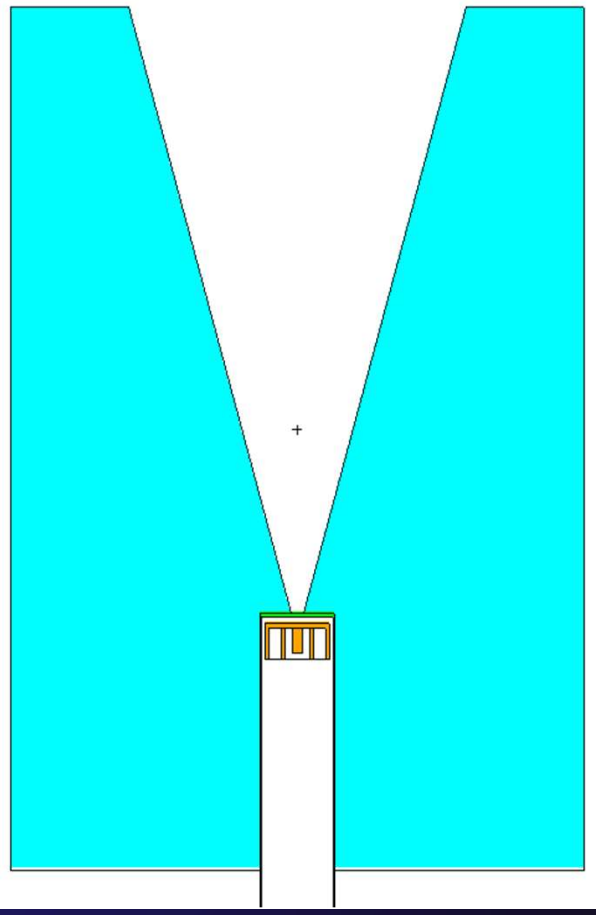
- Measurement of the efficiency of an MCNP calculation:

$$FOM = \frac{1}{R^2 T}$$

  - R is the Relative Error. R $\propto \frac{1}{\sqrt{N}}$
  - T is the time. T $\propto$ Number of Histories
  - FOM should remain constant with an increased number of tallies

Accelerator Information

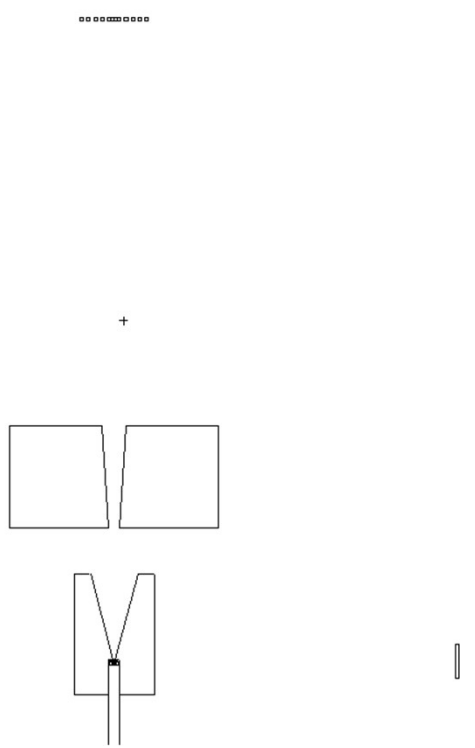
- Energy of Starting Electron: 6 MeV
- Target: Tungsten
- Modeled Based on Varex K15 Linatron



Tallies Used

- F4 Average Cell Flux Tallies

- Leakage to side of target measured with 10x10x1 cm target
- 12 1x1x1 cm tallies 2m forward from target along the beam
  - Used two of these for most comparisons, referred to as “Side” and “Beam”
- Structured mesh tally for visualization of the results



MCNP

- Interactive Plotter

```
@ PATH C:\MY_MCNP\MCNP_CODE\bin;%PATH%
@ set DATAPATH=C:\MY_MCNP\MCNP_DATA
@ set DISPLAY=localhost:0
mcnp6 r=Li20r n=plotter z notek com=plotcom plotm=Run20
del plottero
del plotterc
pause
```

```
fmesh 4
zlev .1 2.5e9
fmrelerr
end
end
```

MCNP Pitfalls

- Results from an MCNP run are solely the mean of the selected tallies and their associated error
  - Selection of the right tallies is important
- There is guidance on what is acceptable relative error from a particular run
  - 10% generally considered acceptable
  - 5% for point detectors
- There is not so much acceptable guidance on what is acceptable difference when using Variance Reduction techniques

- Project: VR technique tallies were compared against the tally from the Analog run to determine if the results were acceptable

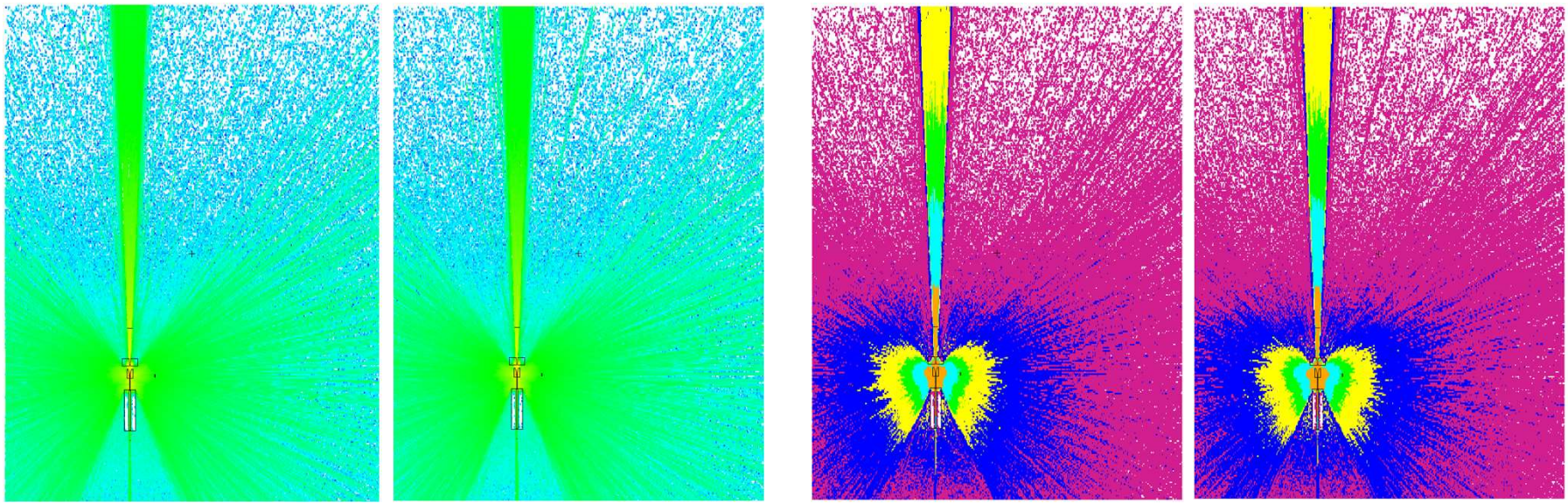
Variance Reduction Techniques

- Truncation
  - Geometry
  - Energy
  - Removing physics
- Modified Sampling
  - Bremsstrahlung Biasing
- Population Control
  - Russian Roulette of low-energy particles
- Partially Deterministic
  - Forced Collisions

Truncation

- Truncation is cutting some part of the simulation off
- This can be performed in many ways:
  - Cutting off the geometry or complications to the geometry
  - Cutting off the simulation at energies, whether low or high
  - Cutting off by time
  - Simplification of simulation
- Risk removal of parts of the problem that are actually important
- Cut cards: remove particles from the simulation based upon energy
  - Default: 1 keV for electrons and photons for Analog MCNP

Truncation - Knock-on Electrons Off



Truncation - Knock-on Electrons Off

Technique	ctm (min)	Leakage FOM	Side FOM	Beam FOM	Faster than Analog By	Leakage Percent Deviation from Analog	Side Percent Deviation from Analog	Beam Percent Deviation from Analog
Analog	70700.47	0.029	0.00041	0.0066	1	0	0	0
Knock-on Off	7566.82	0.27	0.0041	0.066	9.34348	-0.02920774	-11.4712	5.876341

Truncation – Electron Cut Cards

- From Olsher:

$$E_{cut} = 0.25E_{max}$$

For 6 MeV electrons: Ecut = 1.5 MeV

$$E_{cut} = 0.25E_c$$

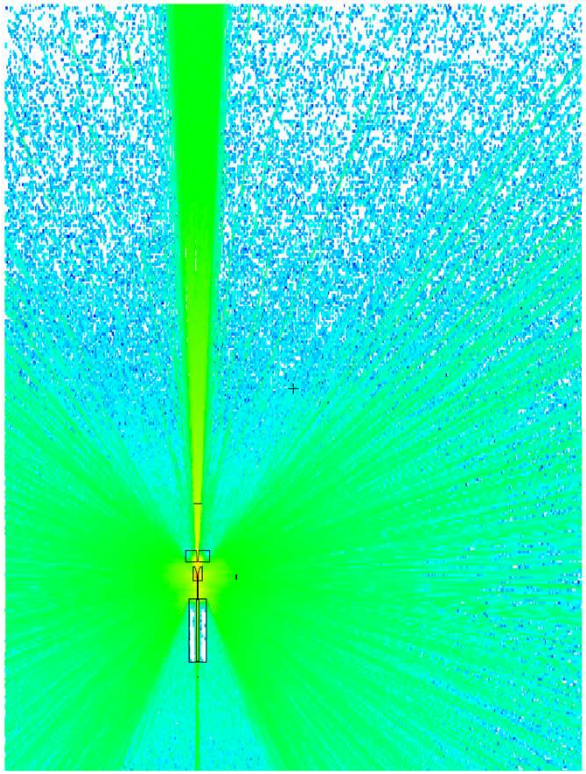
$$E_c = \frac{800}{Z + 2}$$

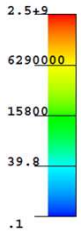
For Tungsten: Ecut = 2.6 MeV

- Tested cut:e of 1.5, 3.75 MeV

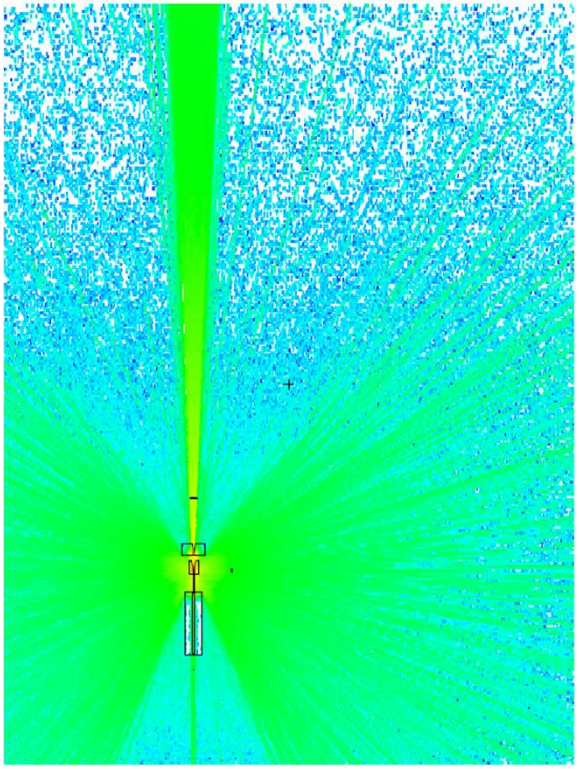
Truncation – Electron Cut Cards

Analog

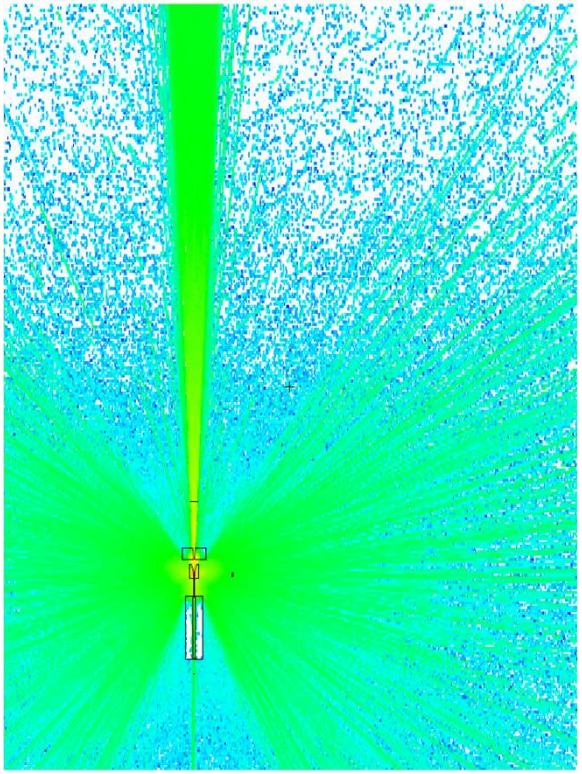




1.5 MeV

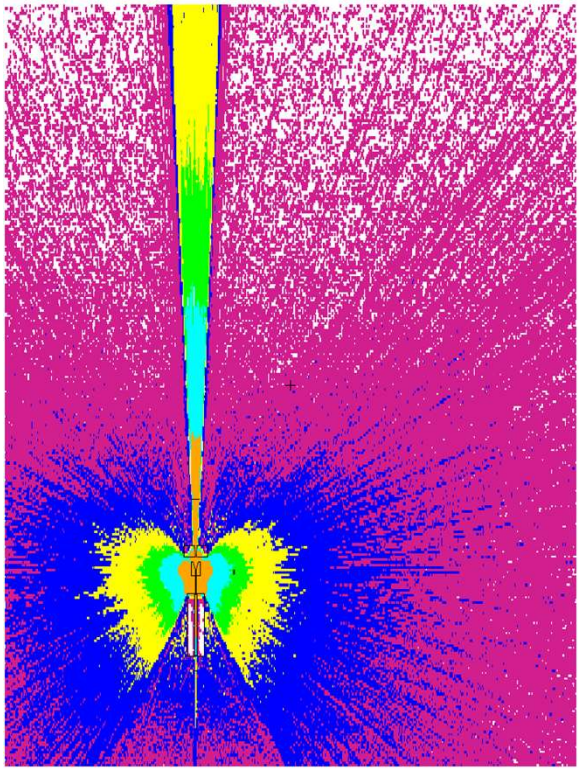


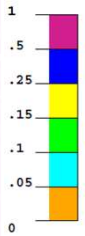
3.75 MeV



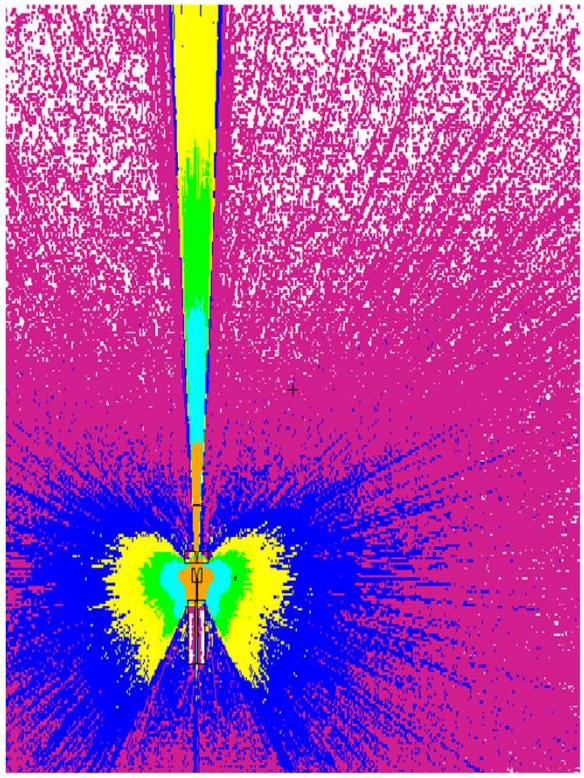
Truncation – Electron Cut Cards

Analog

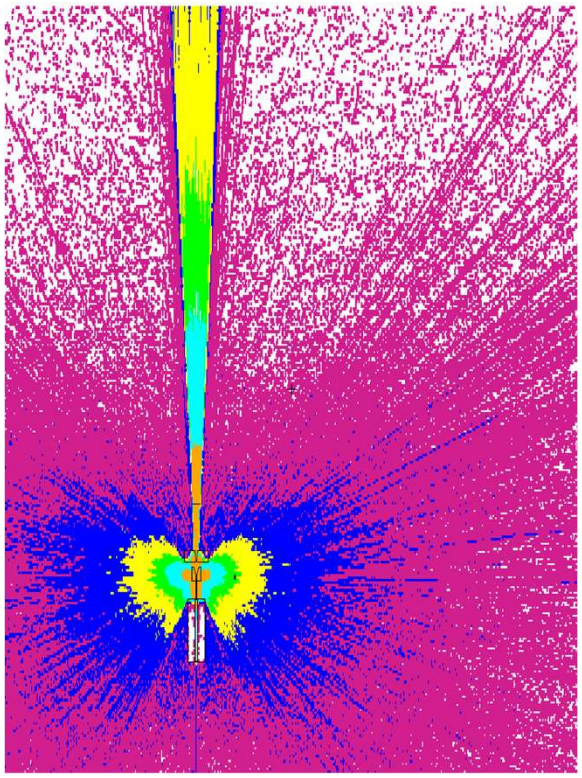




1.5 MeV



3.75 MeV

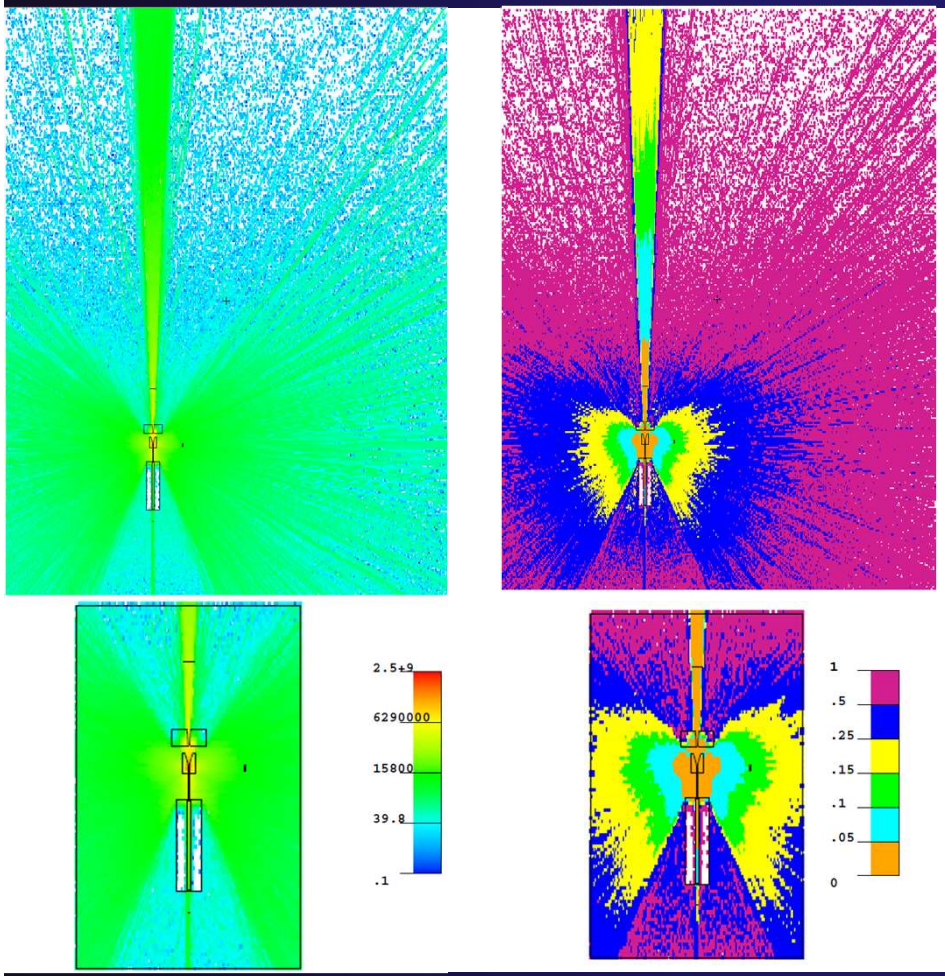


Truncation – Electron Cut Cards

Technique	Computer Time (min)	Leakage FOM	Side FOM	Beam FOM	Speed Change	Leakage Percent Deviation from Analog	Side Percent Deviation from Analog	Beam Percent Deviation from Analog
Analog	70700.47	0.029	0.00041	0.0066	1	0	0	0
Electron Cut 1.5 MeV	469.69	4.4	0.057	0.99	150.52	2.5483	-3.25639	-0.6457
Electron Cut 3.75 MeV	207.88	6.2	0.12	2.1	340.10	-31.4706	-11.0631	-6.5731

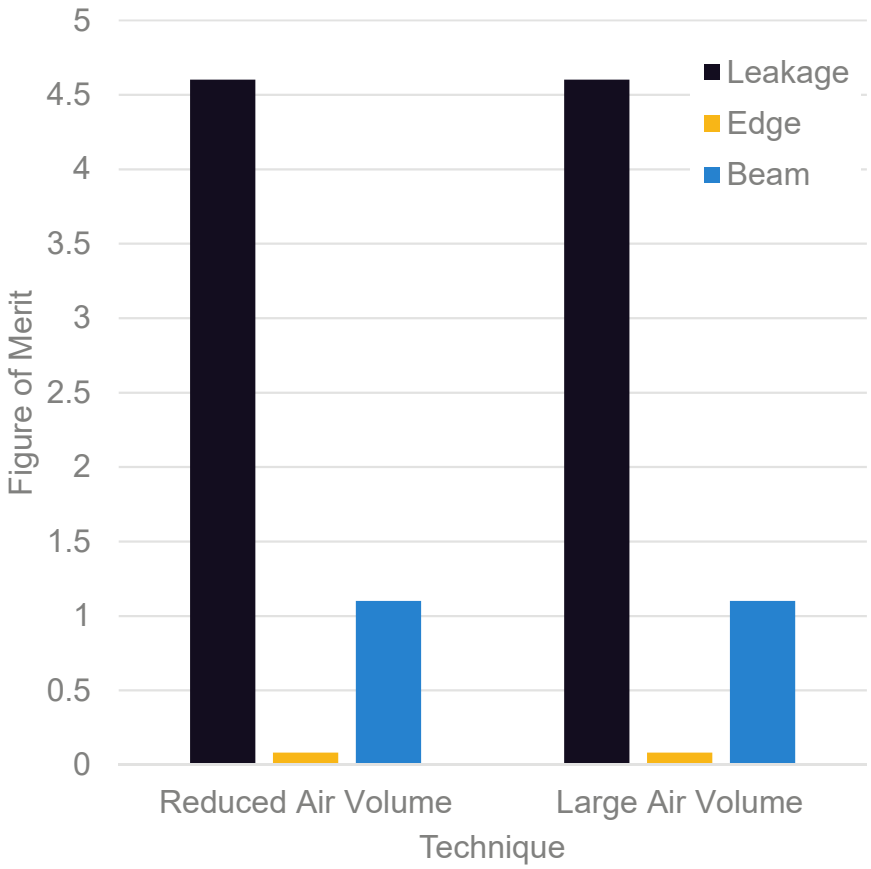
- Take care with the appropriate electron cut card

Truncation - Geometry



- Initial Geometry:
  - 53900x44500x22100 cm
- Reduced Geometry:
  - 402x652x249 cm
- Geometry reduced to 1 m beyond edges of detectors or accelerator geometry
- No longer simulated particle transport through large additional volume of air

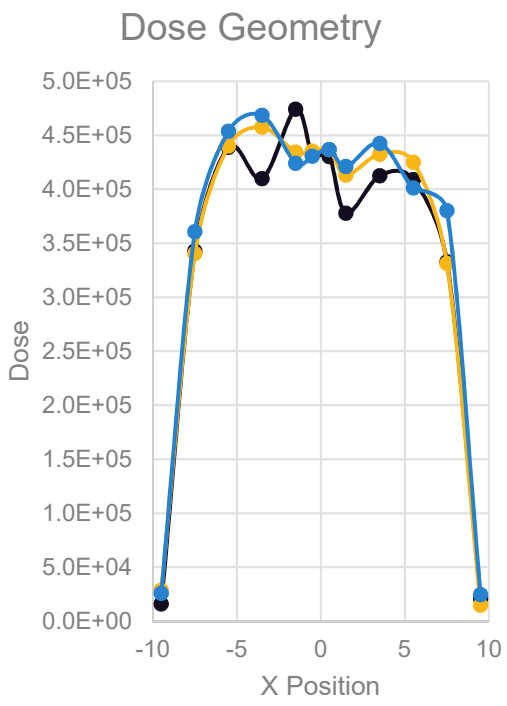
Truncation - Geometry

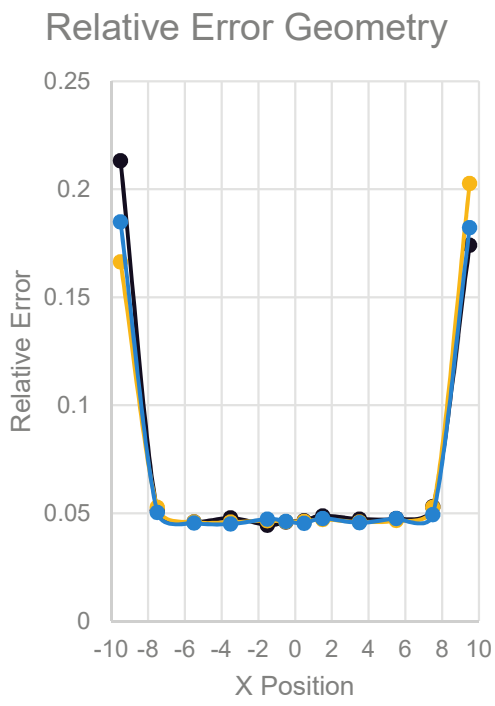


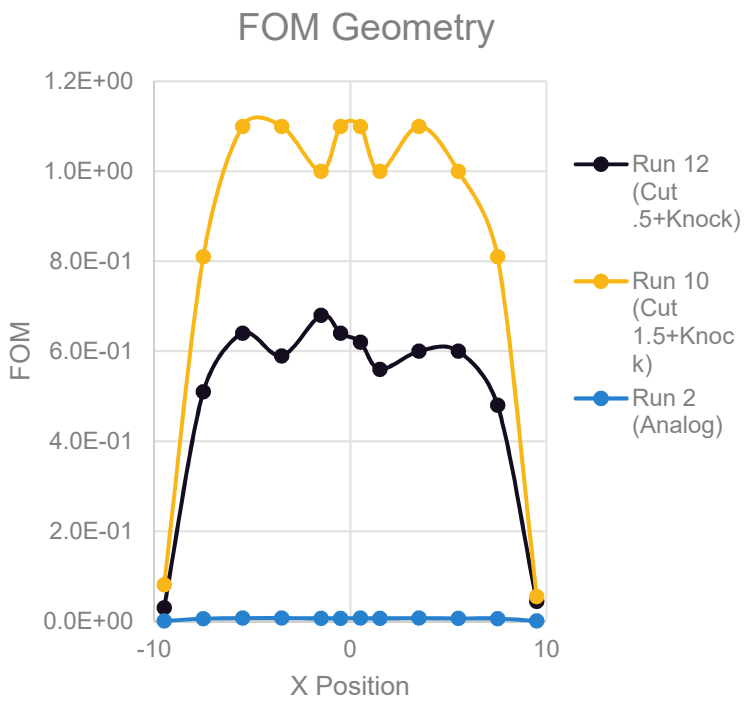
- Initial Geometry:
  - 53900x44500x22100 cm
- Reduced Geometry:
  - 402x652x249 cm
- Results:
  - Little gain in Figure of Merit
  - Excess air volume did not affect this run and would not be an important avenue for optimization

Truncation

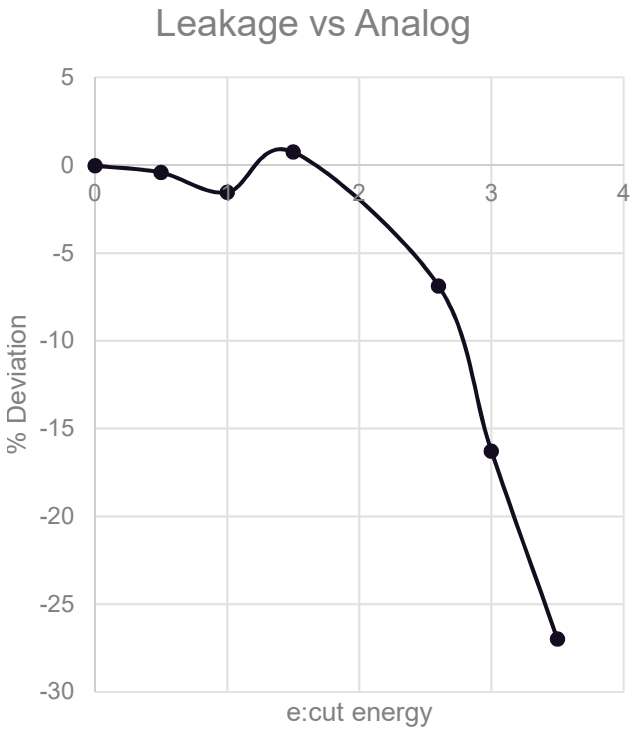
Additional runs performed combining electron cut cards and knock-on off

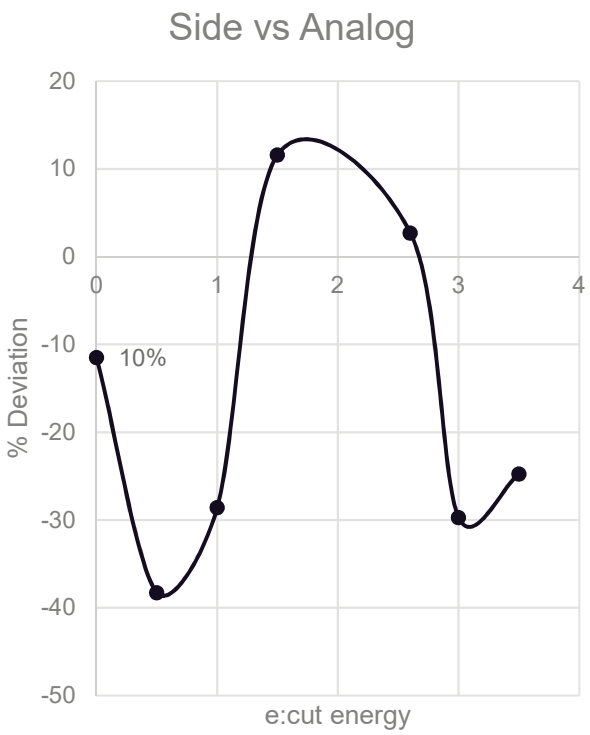


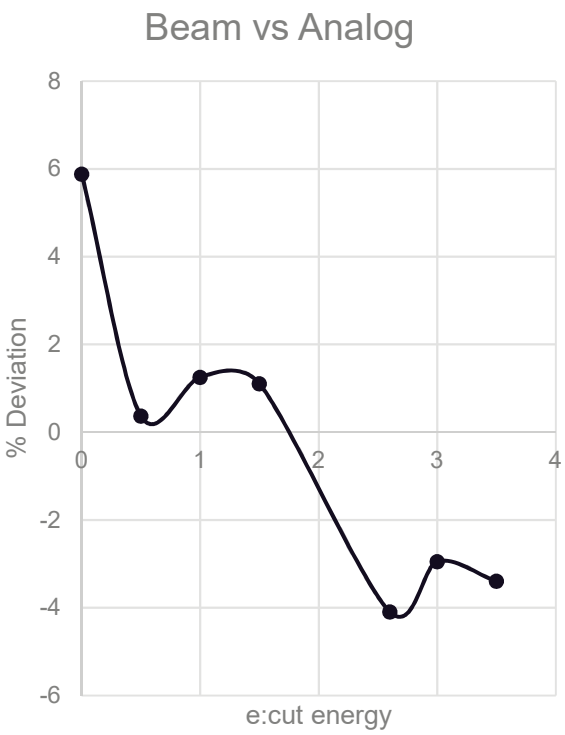




Truncation - Combined







Additional runs performed combining electron cut cards and knock-on off

Truncation – Photon Cut Card

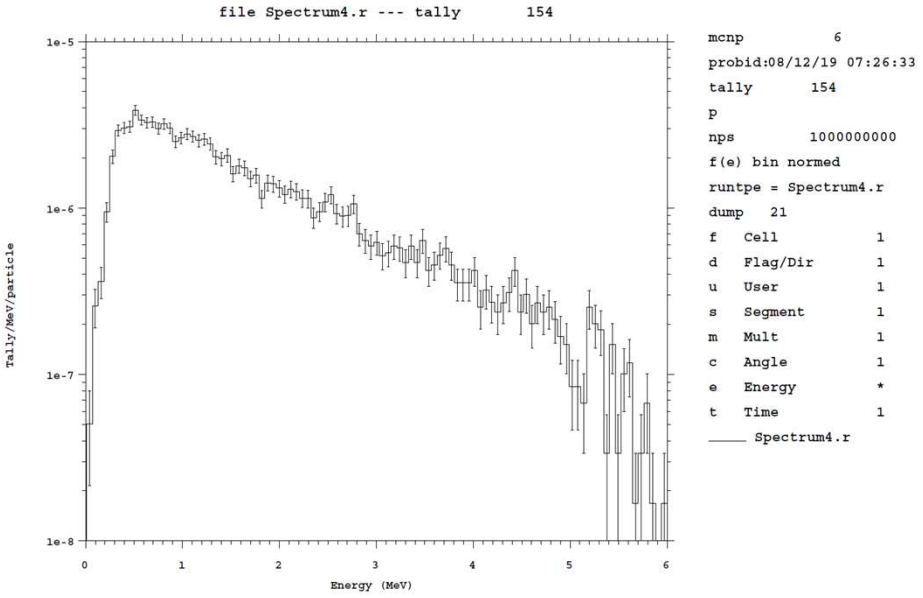
- Tested cut:p of 0.015 MeV

Technique	Time (min)	Leakage Relative Error	Leakage FOM	Side Relative Error	Side FOM	Beam Relative Error	Beam FOM
Analog	70700.47	0.0219	0.029	0.1849	0.00041	0.0463	0.0066
Photon Cut 15 keV	69850.27	0.0218	0.03	0.2068	0.00033	0.0457	0.0069

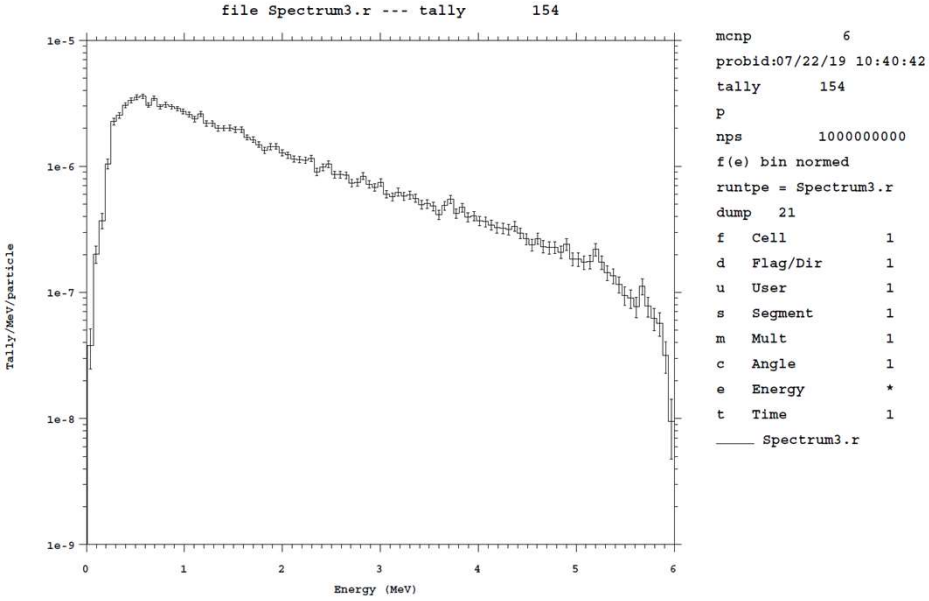
Modified Sampling

- Sampling from a distribution other than the MCNP abstraction that best simulates nature
- Bremsstrahlung Biasing
  - Higher energy photons within a particular material
  - Results in more computer time to perform simulation from these higher energy particles
  - May allow better sampling due to the higher energy particles
  - Biasing factors of 1 to 15 with 46 steps in between
    - Complex normalization by the code of those steps

Modified Sampling – Bremsstrahlung Biasing




```
mcnp          6
probid:08/12/19 07:26:33
tally       154
p
nps         1000000000
f(e) bin normed
runtpe = Spectrum4.r
dump   21
f   Cell          1
d   Flag/Dir      1
u   User          1
s   Segment       1
m   Mult          1
c   Angle         1
e   Energy        *
t   Time          1
____ Spectrum4.r
```




```
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probid:07/22/19 10:40:42
tally       154
p
nps         1000000000
f(e) bin normed
runtpe = Spectrum3.r
dump   21
f   Cell          1
d   Flag/Dir      1
u   User          1
s   Segment       1
m   Mult          1
c   Angle         1
e   Energy        *
t   Time          1
____ Spectrum3.r
```
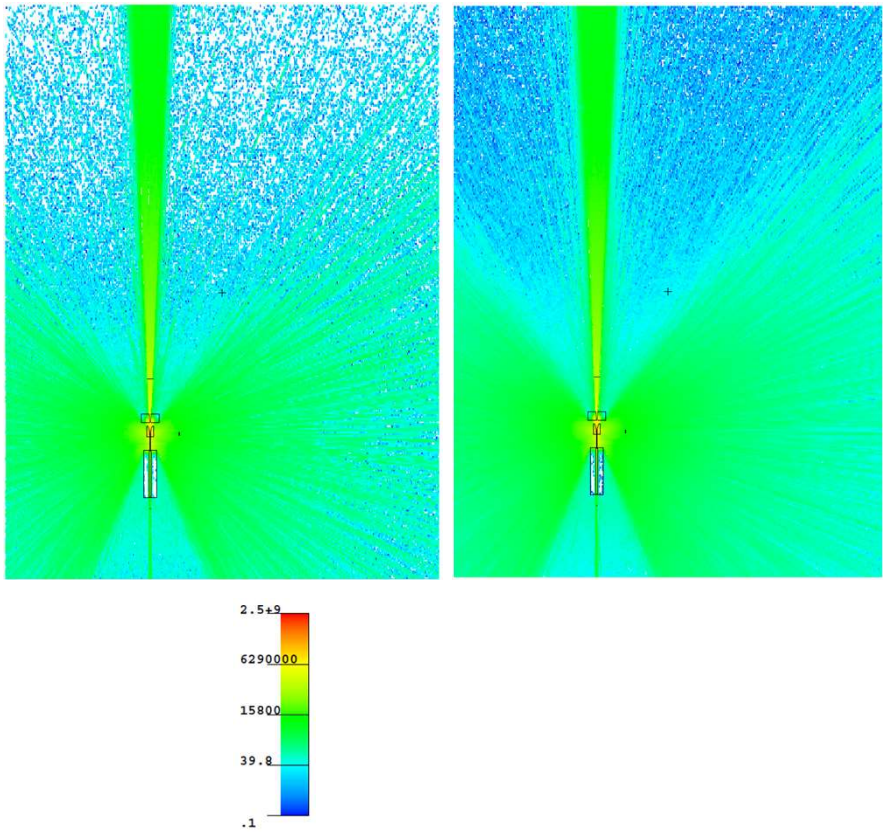
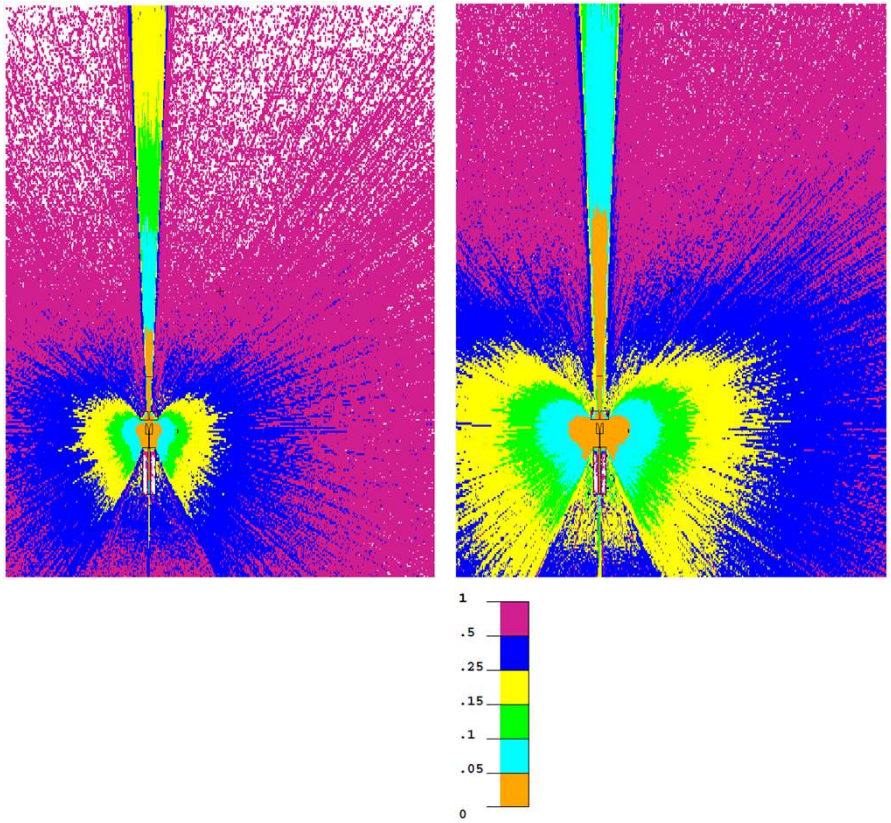

Modified Sampling – Bremsstrahlung Biasing

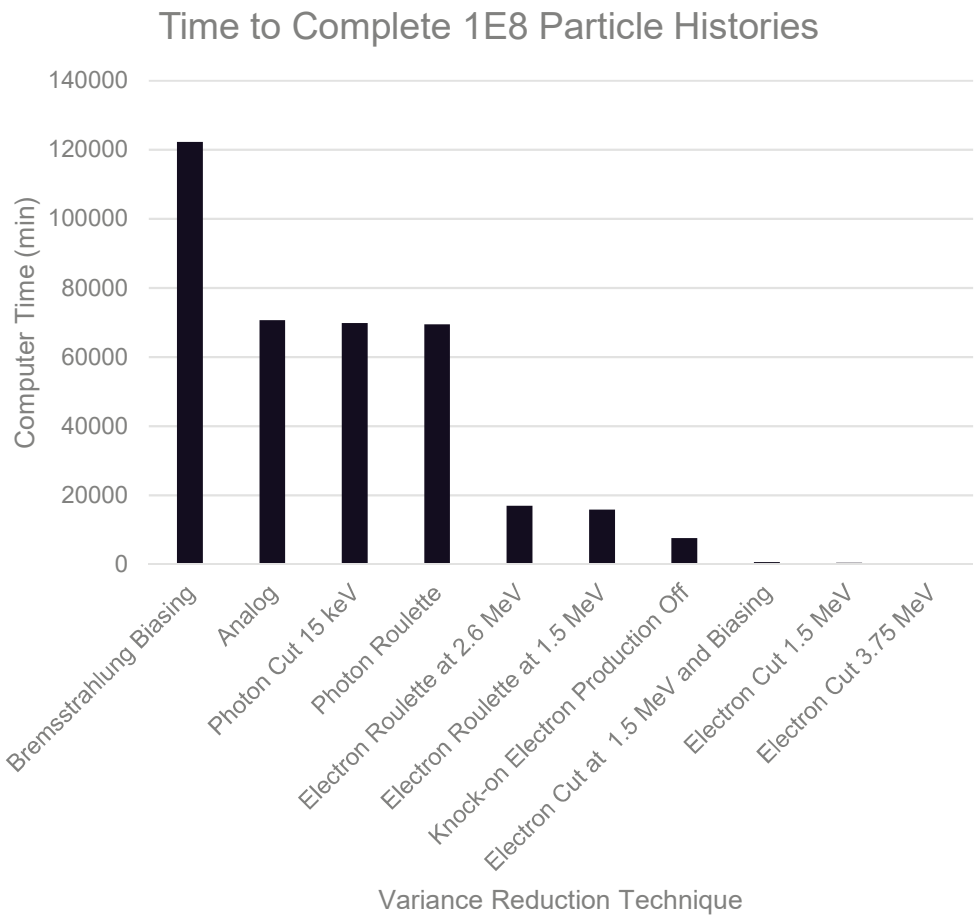
Analog

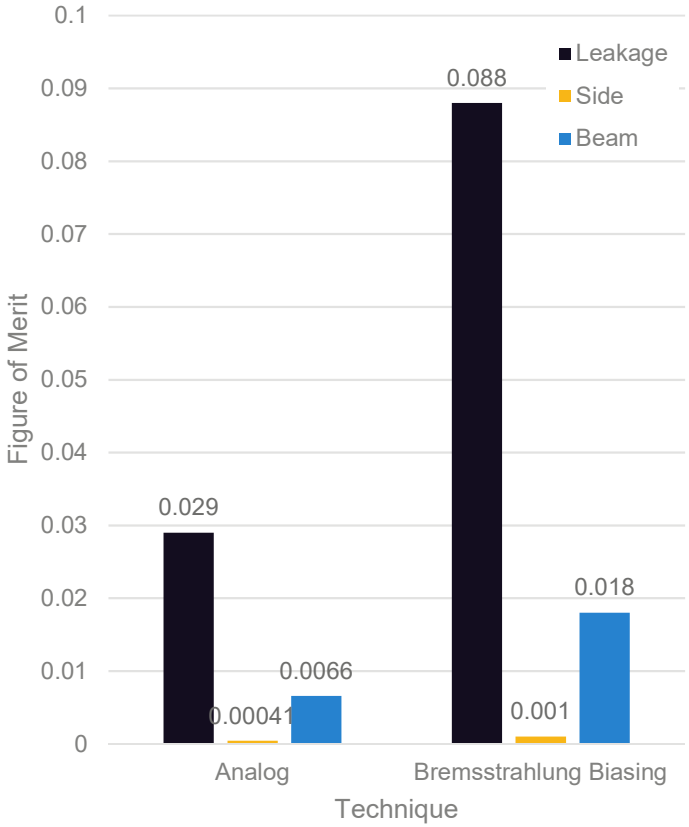
Biased





Modified Sampling – Bremsstrahlung Biasing



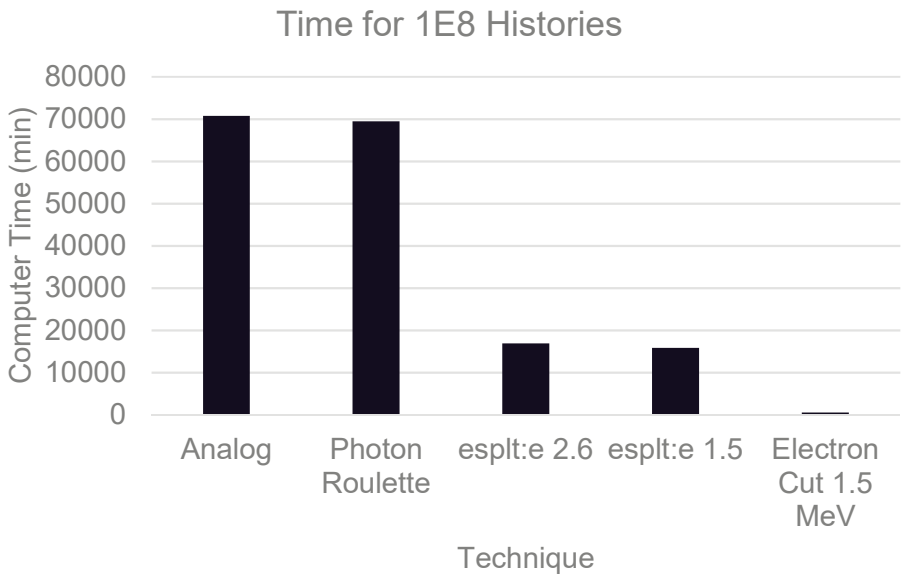


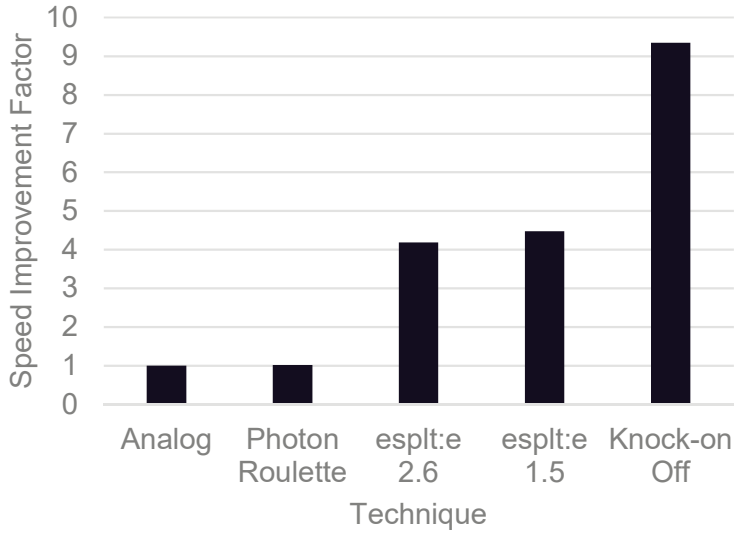
Population Control

- Russian Roulette
  - Provide a probability to kill a particular particle history
  - An additional step undertaken within the particle history
  - Will add time per particle history
  - However, much like the cut cards, will no longer simulate so many histories
- The esplt card, Energy Splitting and Roulette
  - Utilized for electrons
  - Compared against the electron cut card
  - Lower risk of removing something important than truncation

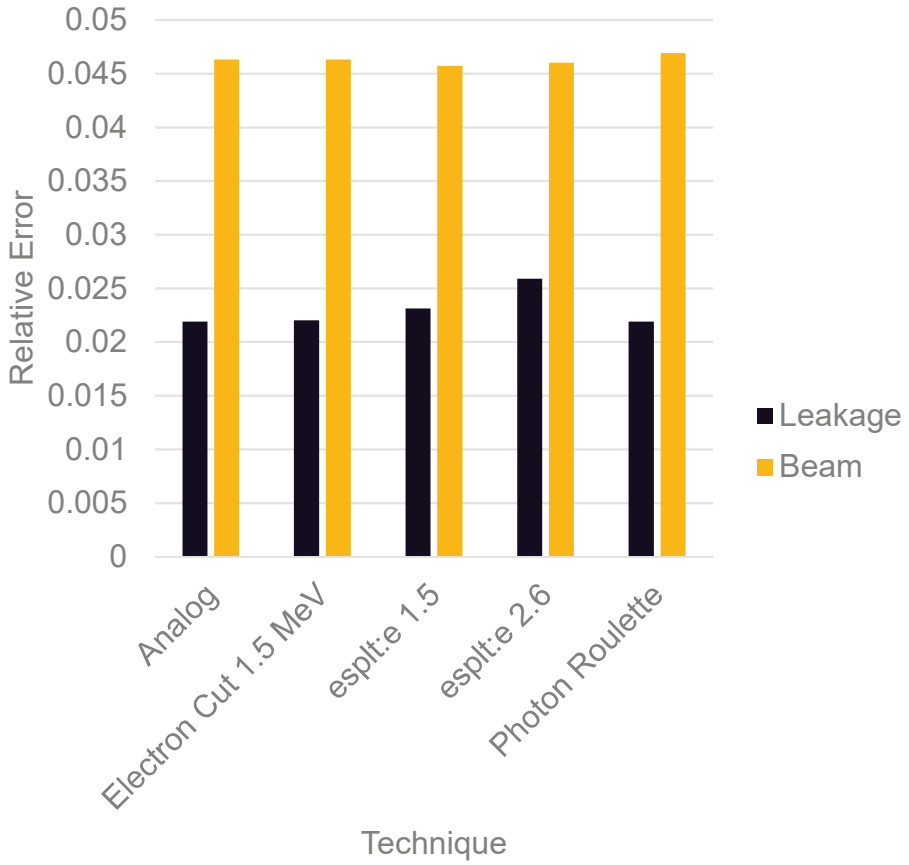
Population Control - esplt

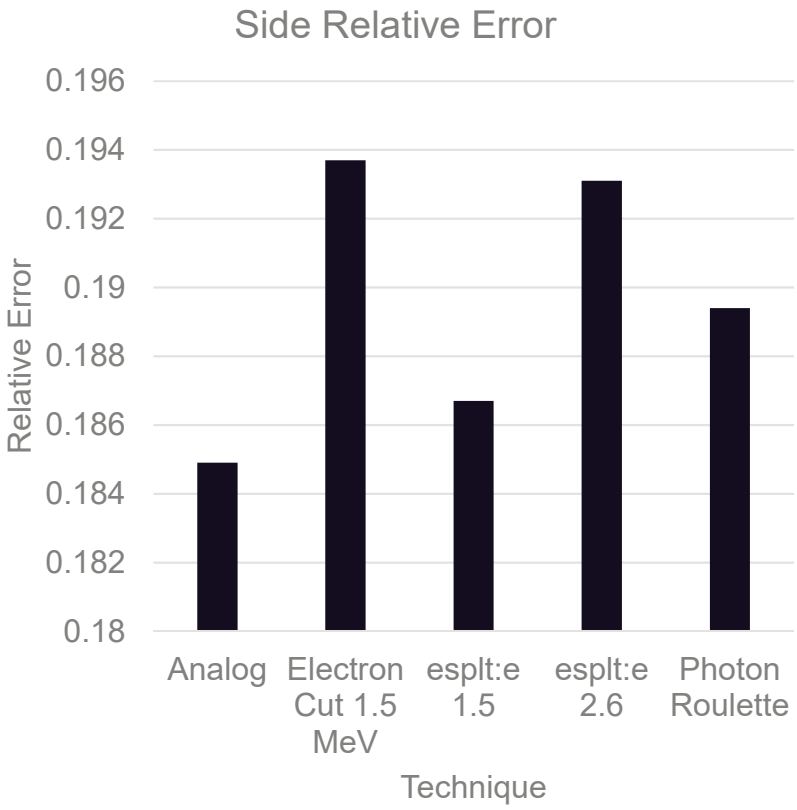
- Two variations on the esplt tested:
  - esplt:e 0.5 1.5 0.1 0.5 (50% below 1.5 MeV, 10% below 0.5 MeV)
  - esplt:e 0.5 2.6 0.1 1.5 (50% below 2.6 MeV, 10% below 1.5 MeV)



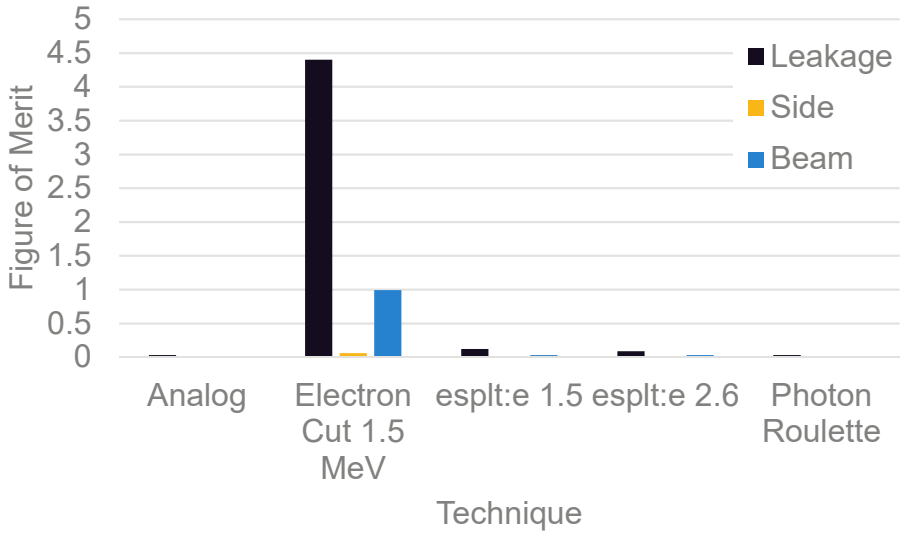


Population Control





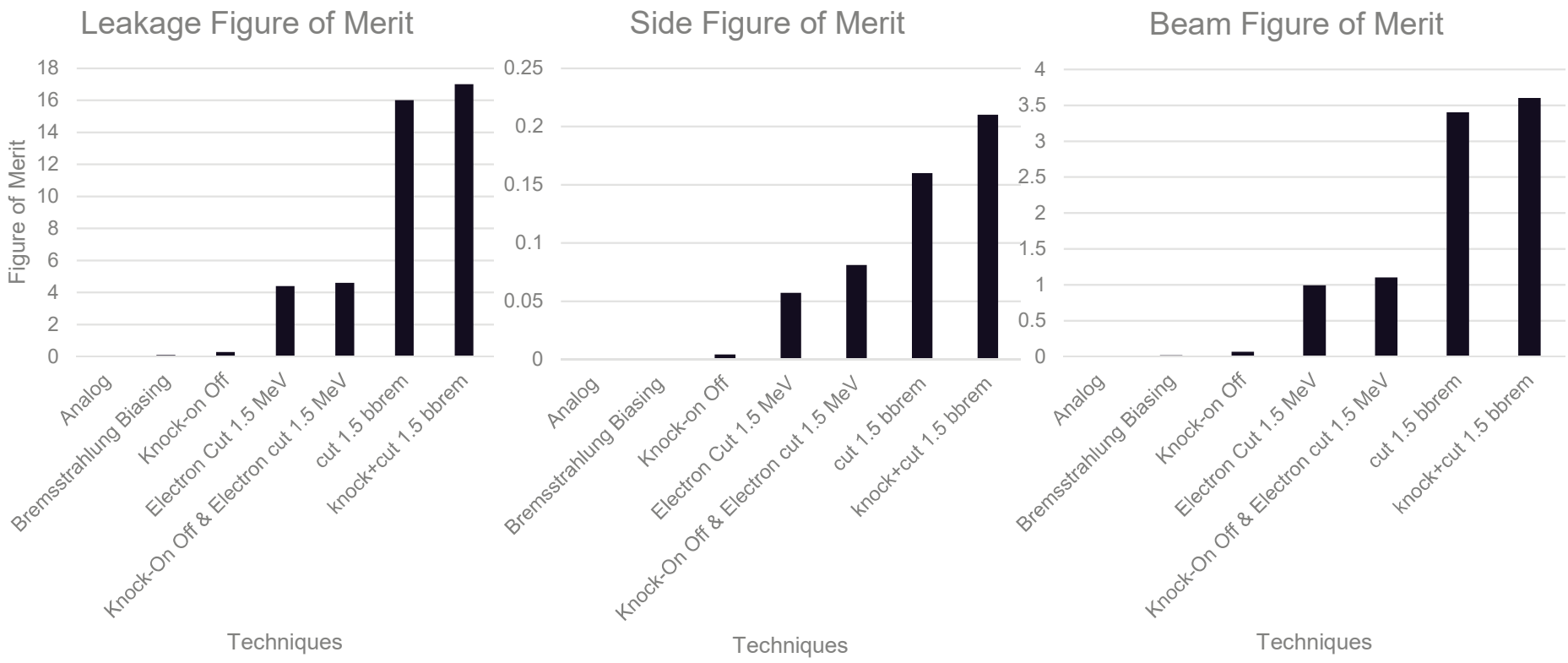
Population Control



Technique	Leakage Dose	Relative Error	Side Dose	Side Relative Error	Beam Dose	Beam Relative Error	Leakage % Deviation from Analog	Side % Deviation	Beam % Deviation
Analog	13695	0.0219	25734	0.1849	430540	0.0463	0	0	0
Electron Cut 1.5 MeV	14044	0.022	24896	0.1937	427760	0.0463	2.55	-3.26	-0.646
esplt:e 1.5	13710	0.0231	24686	0.1867	455180	0.0457	0.110	-4.07	5.72
esplt:e 2.6	14339	0.0259	22780	0.1931	453770	0.046	4.70	-11.5	5.40

Combining Techniques

- Electron Cut Card, Bremsstrahlung Biasing, and Knock-on Off



Partially Deterministic

- DXTRAN spheres
- F5 Point Detectors

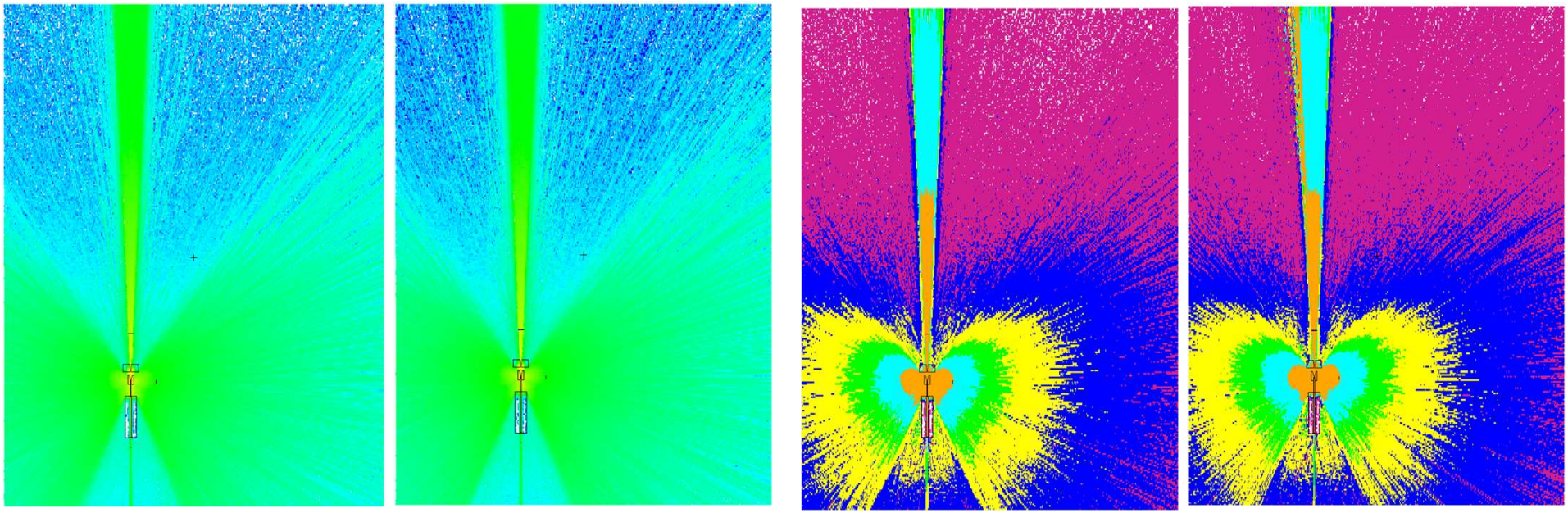
- Would likely add value in more complex geometries with particular important locations, for problems like streaming.

- Circumvent normal random walk process to increase scoring efficiency
  - Use of pseudoparticles for this requires additional time

Partially Deterministic

Cut, Biased, Knock Off

DXTRAN

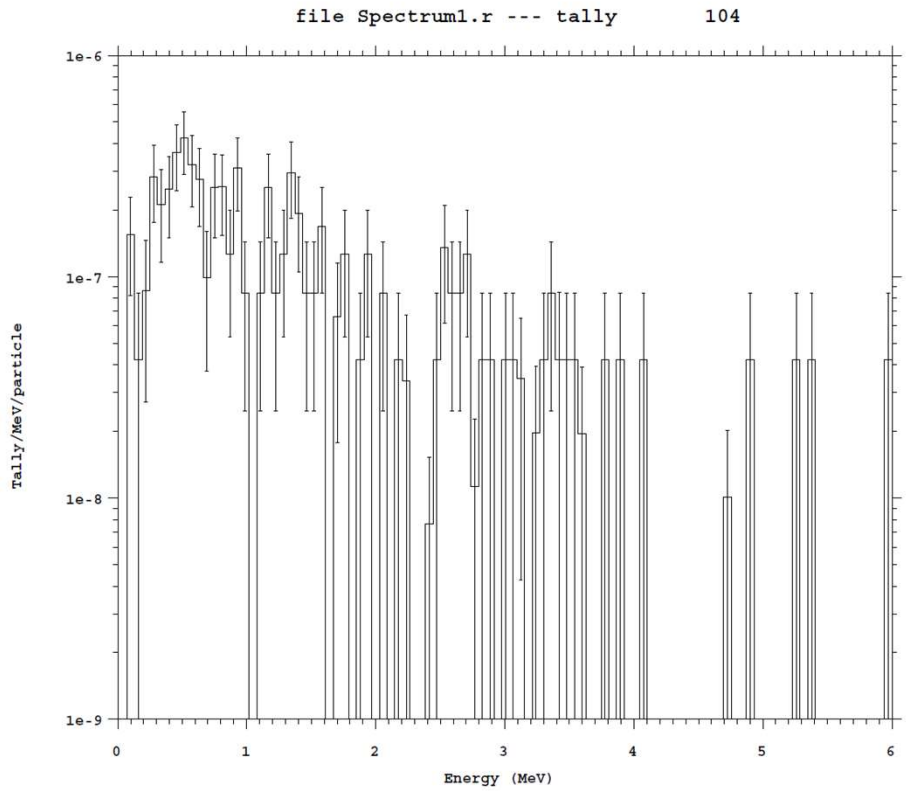


DXTRAN Sphere was placed over the high-error tally at the side of the beam

Partially Deterministic

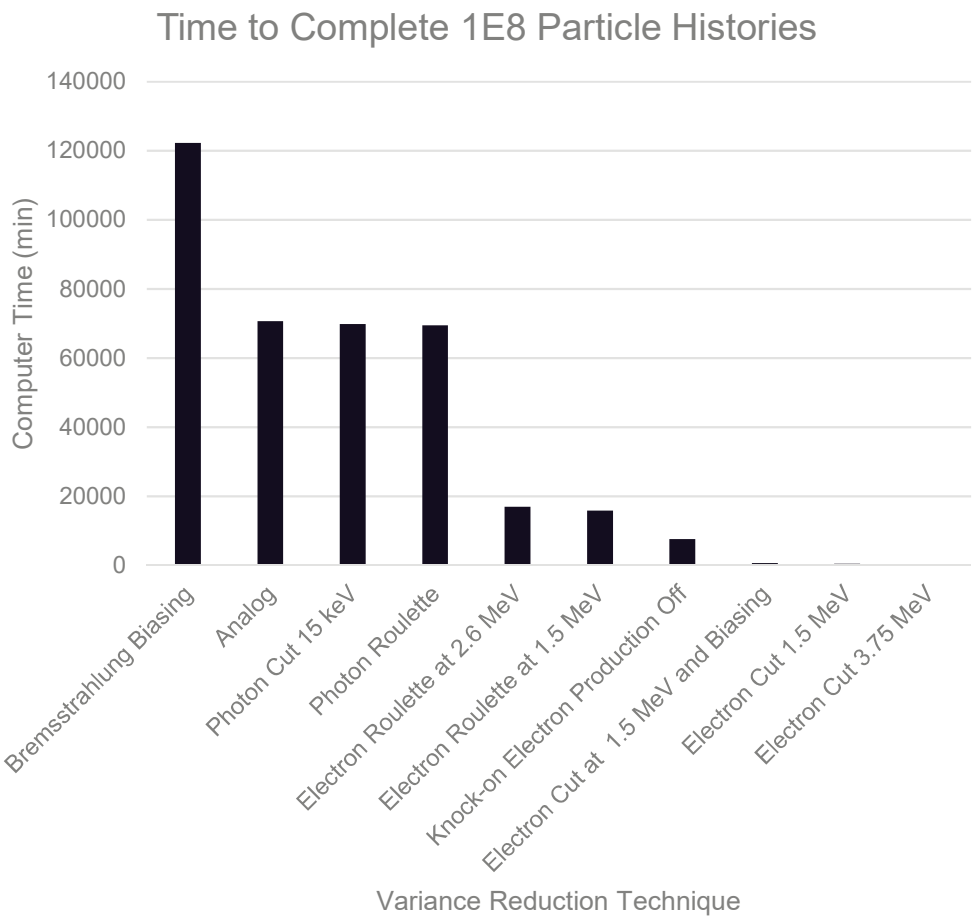
Technique:	Computer Time	ctm (min)	Dose	Relative Error	FOM	Dose	Relative Error	FOM	Dose	Relative Error	FOM
knock+cut 1.5 bbrem	627.58	616.08	13015.0	0.0098	17	21603	0.0878	0.21	439960	0.0212	3.6
DXT Test	966.28	954.56	13486.0	0.0097	11	20722	0.0038	74	438360	0.0212	2.3

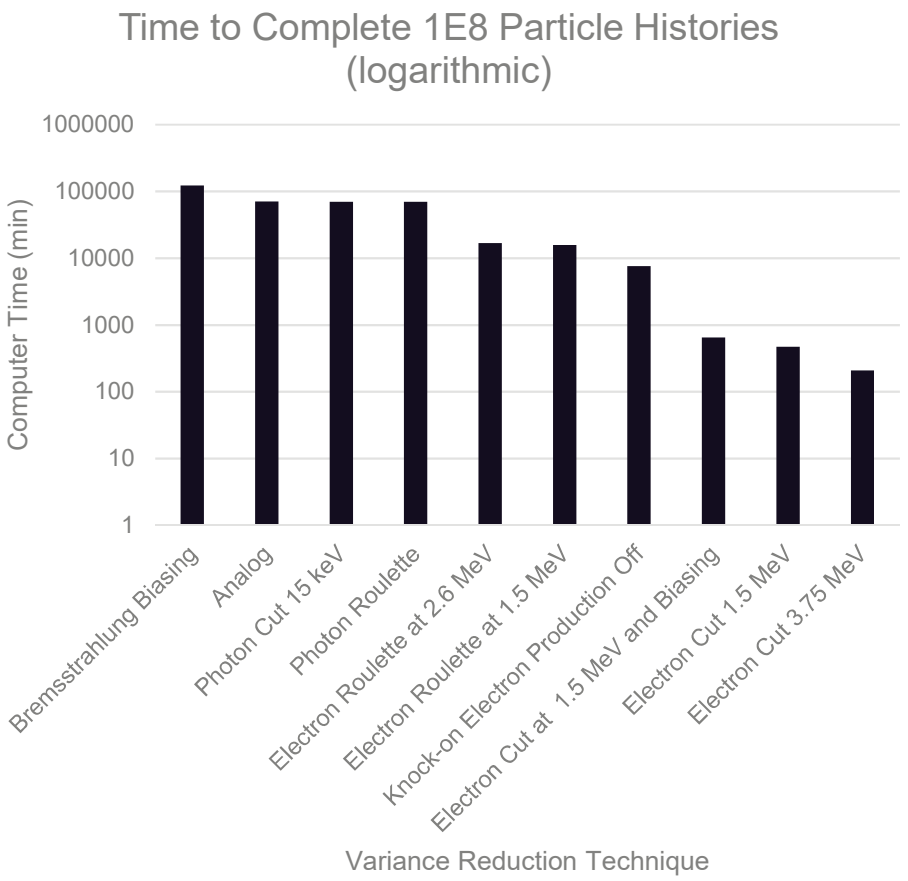
Spectrum Comparison



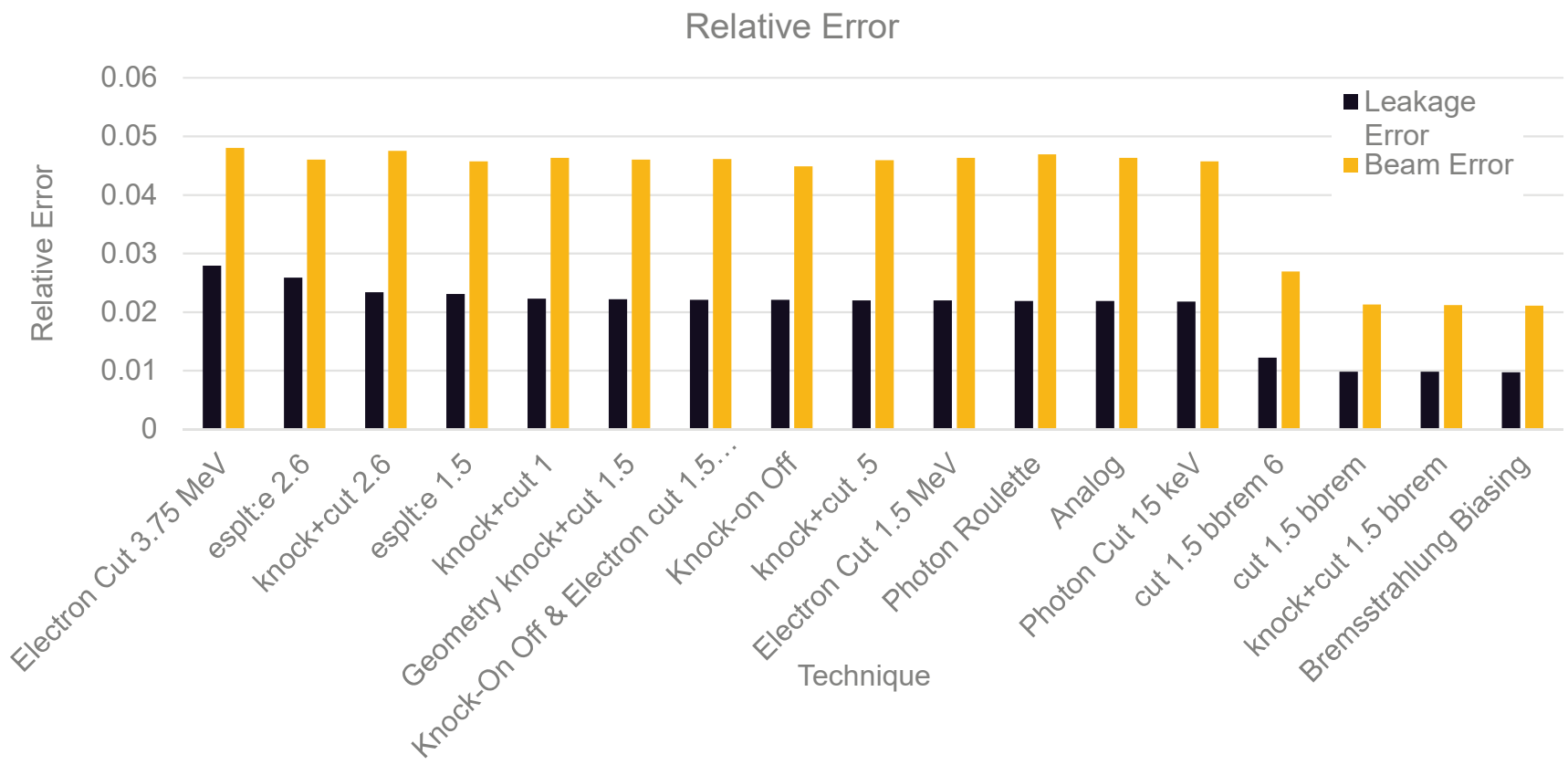

```
mcnp          6
probid:07/22/19 15:06:11
tally       104
p
nps          400000000
f(e) bin normed
runtpe = Spectrum1.r
dump     9
f    Cell            1
d    Flag/Dir        1
u    User            1
s    Segment         1
m    Mult            1
c    Angle           1
e    Energy          *
t    Time            1
_____ Spectrum1.r
```

Computer Time





Relative Error



Relative Error

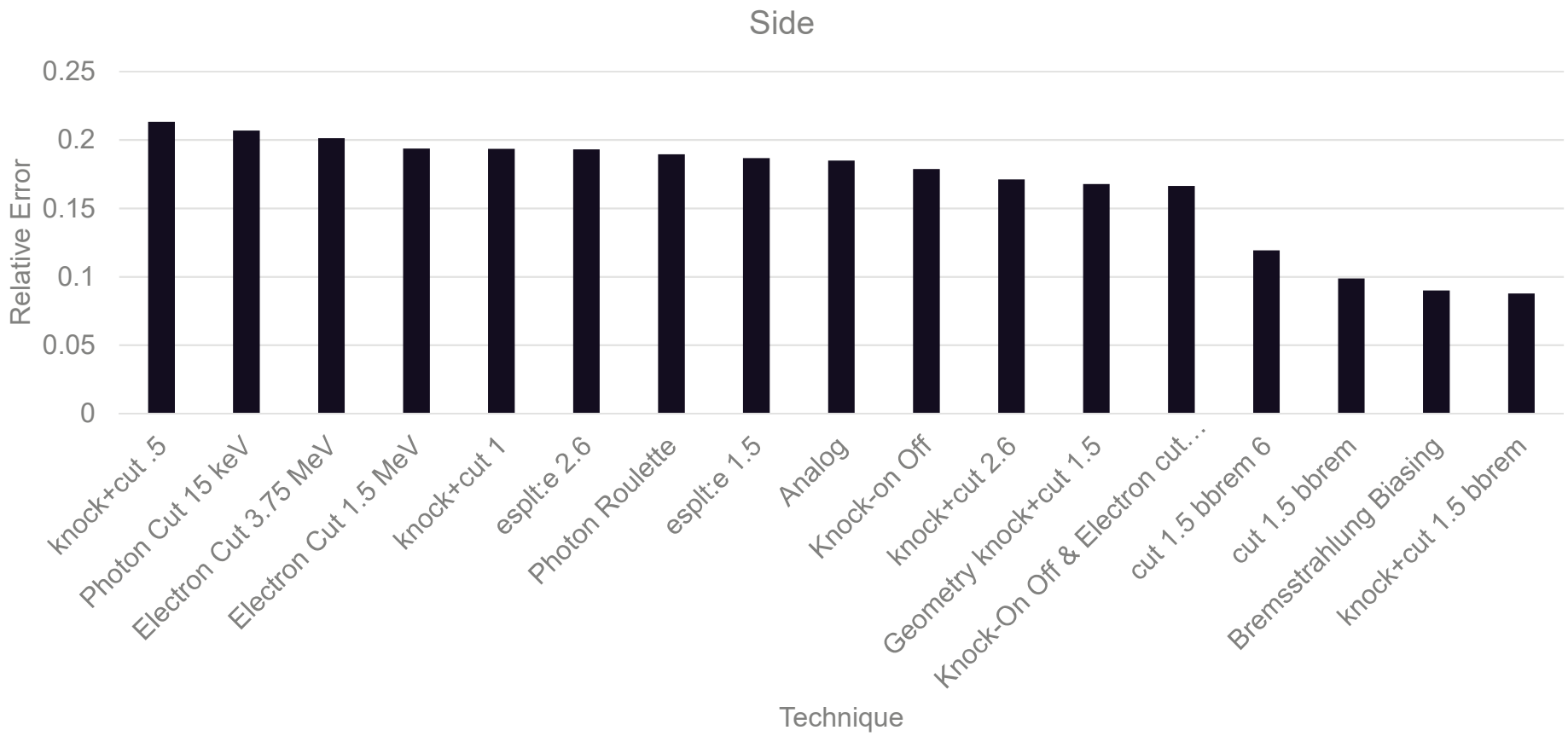


Figure of Merit

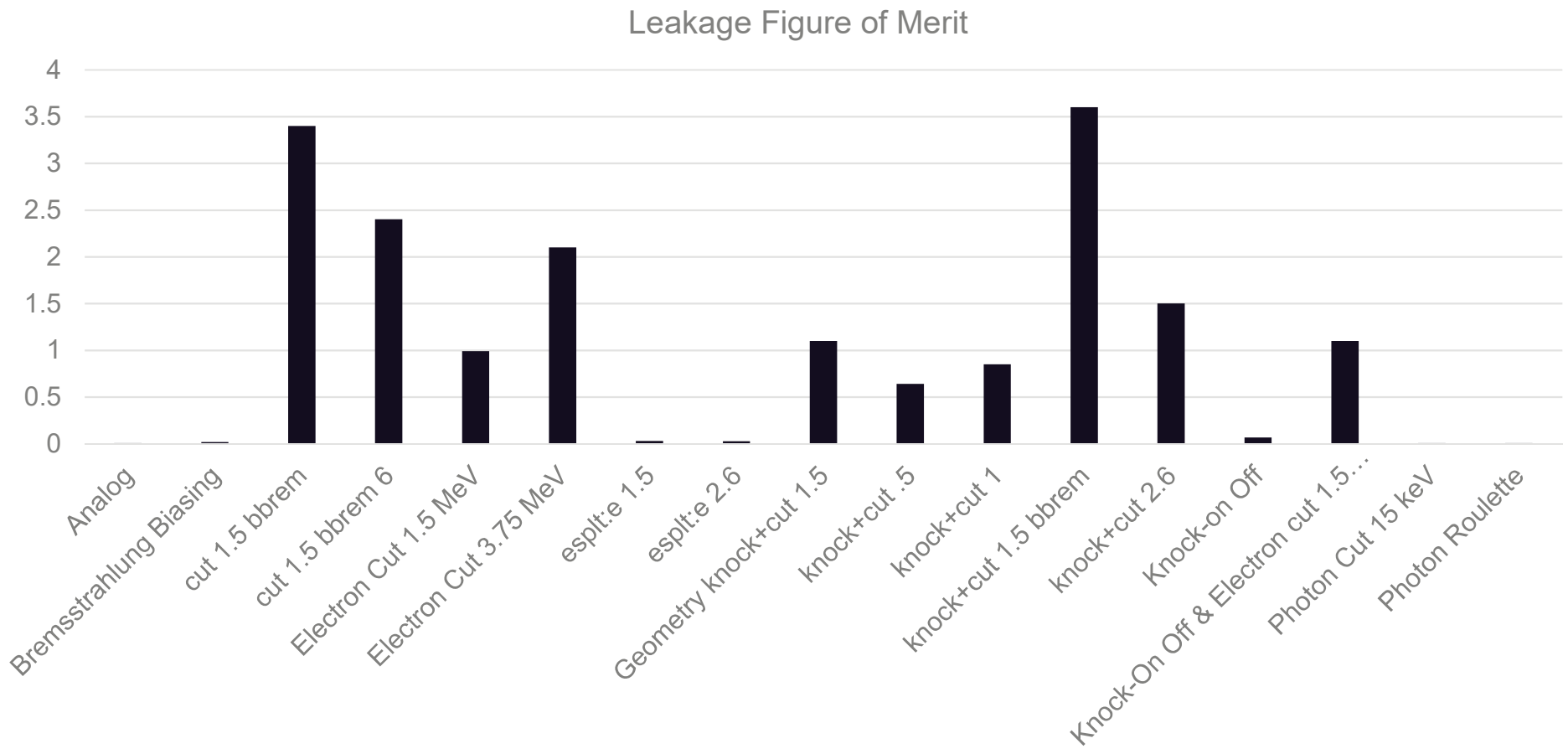
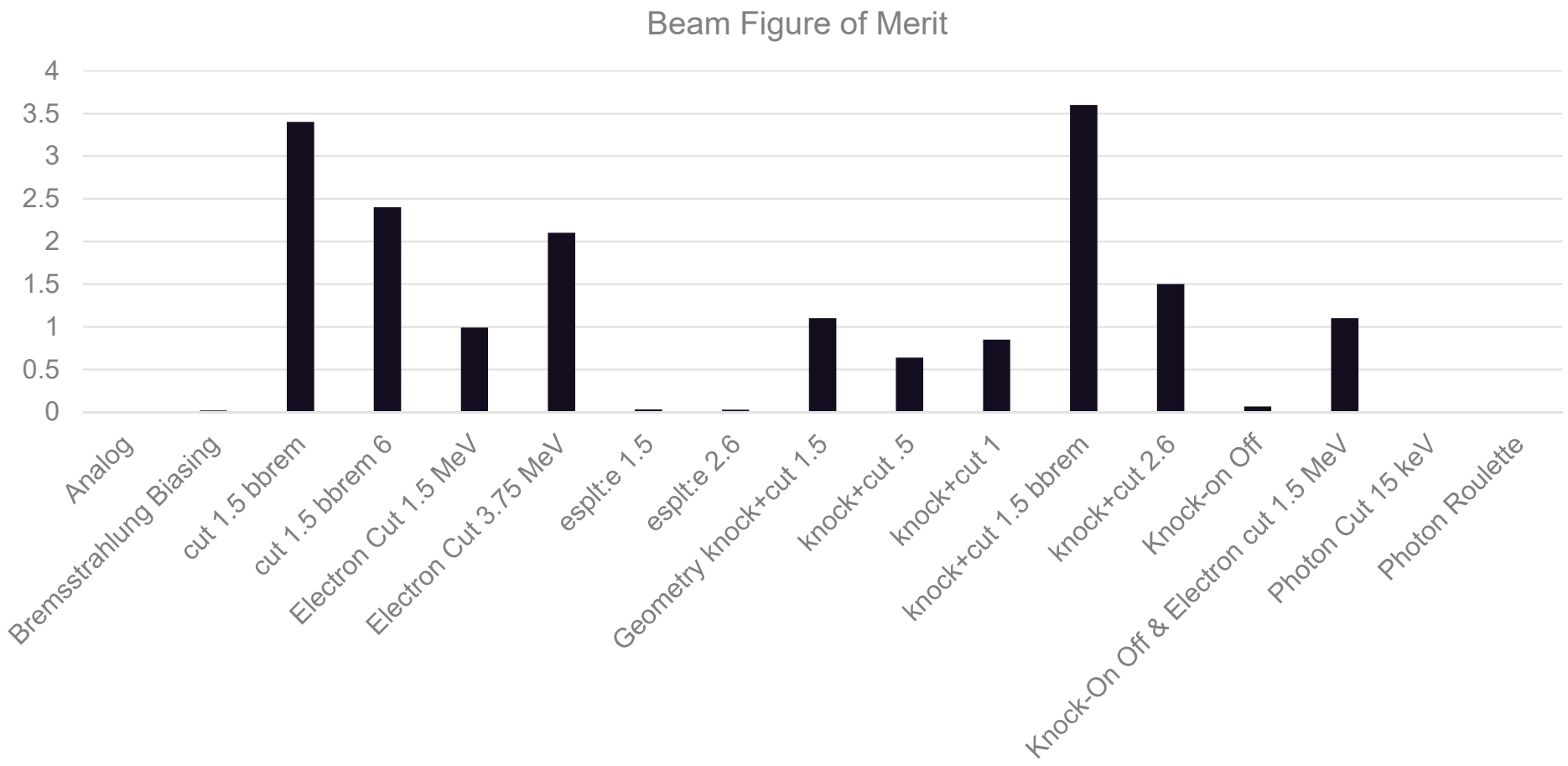
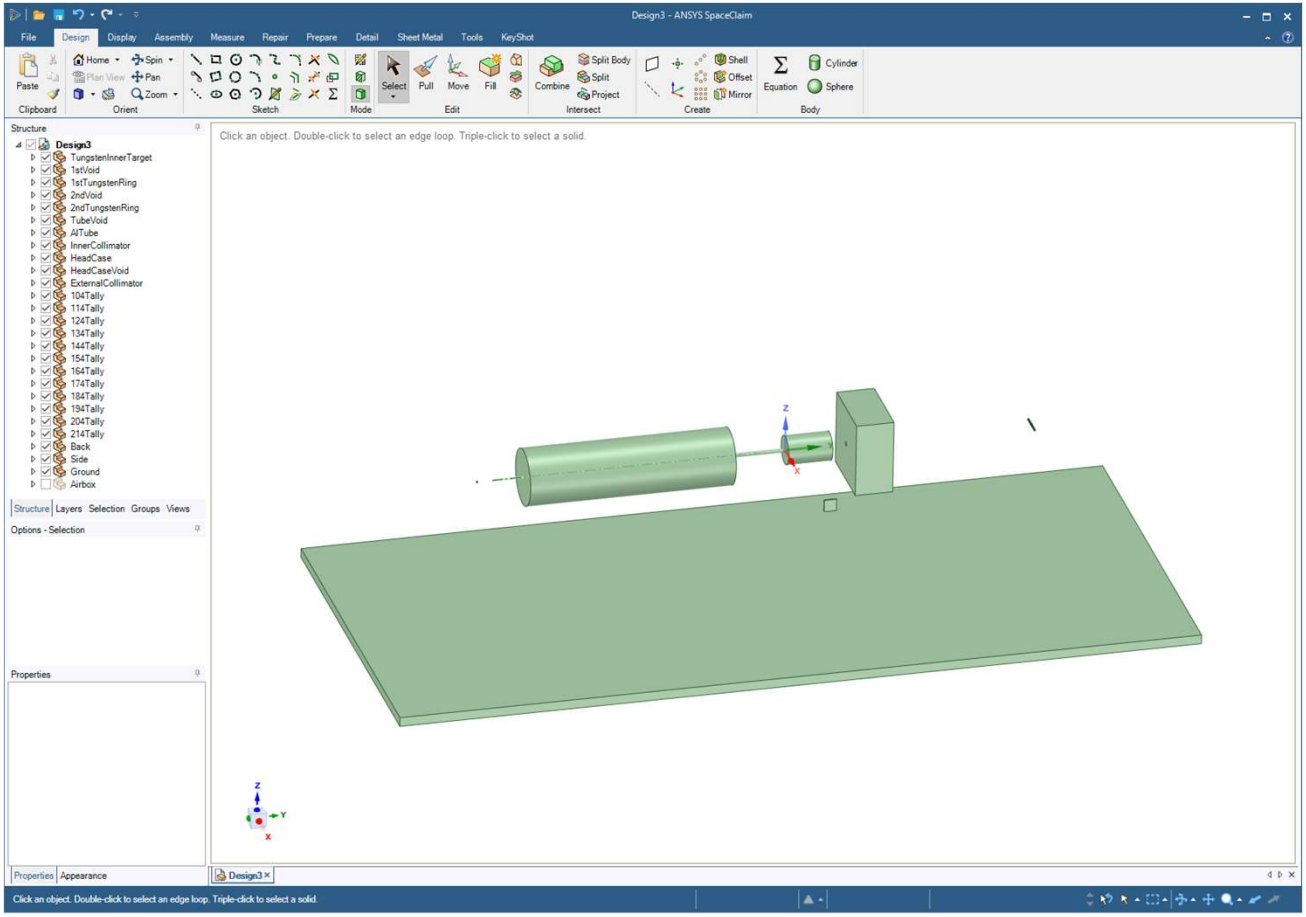


Figure of Merit

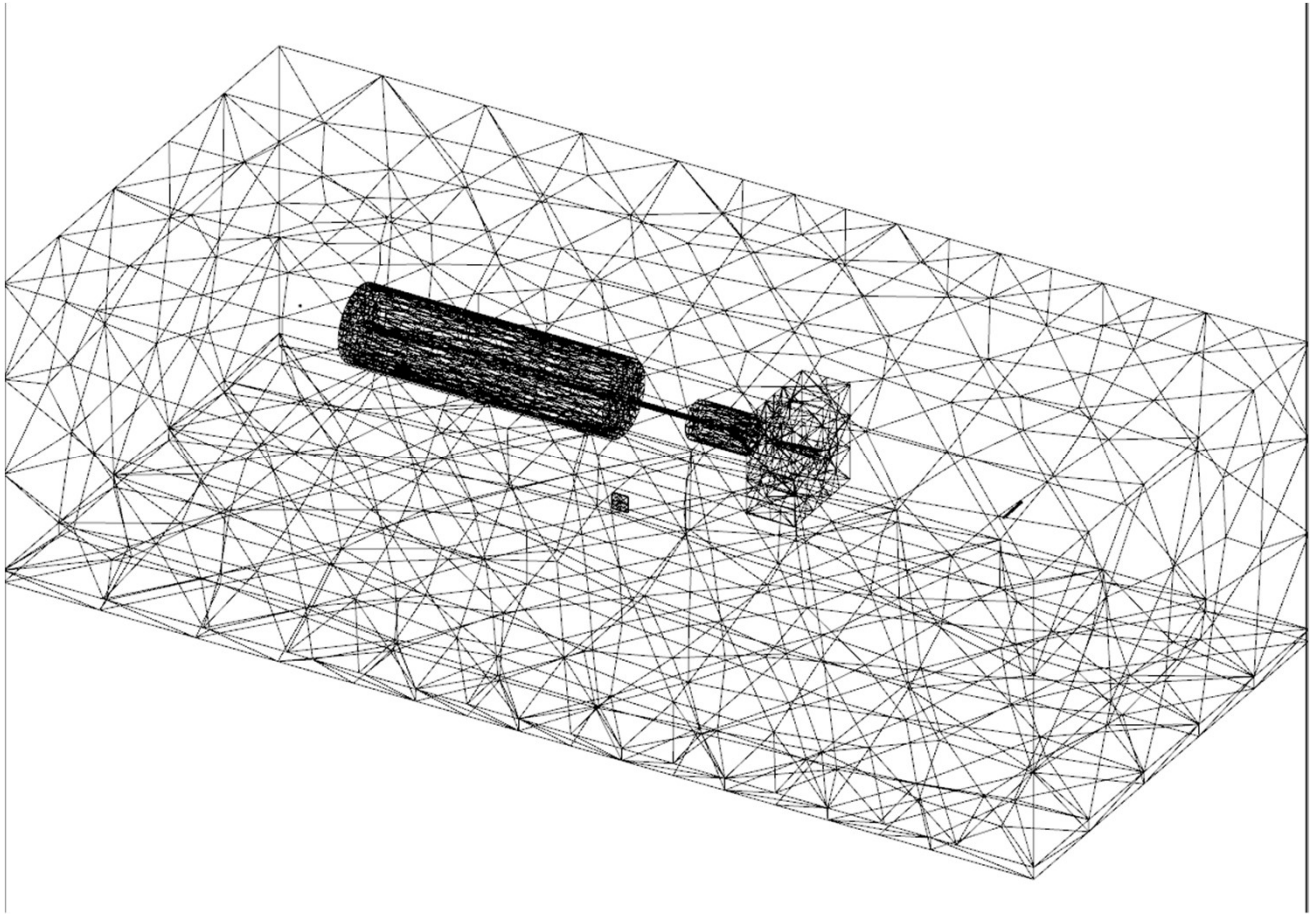


Attila4MC

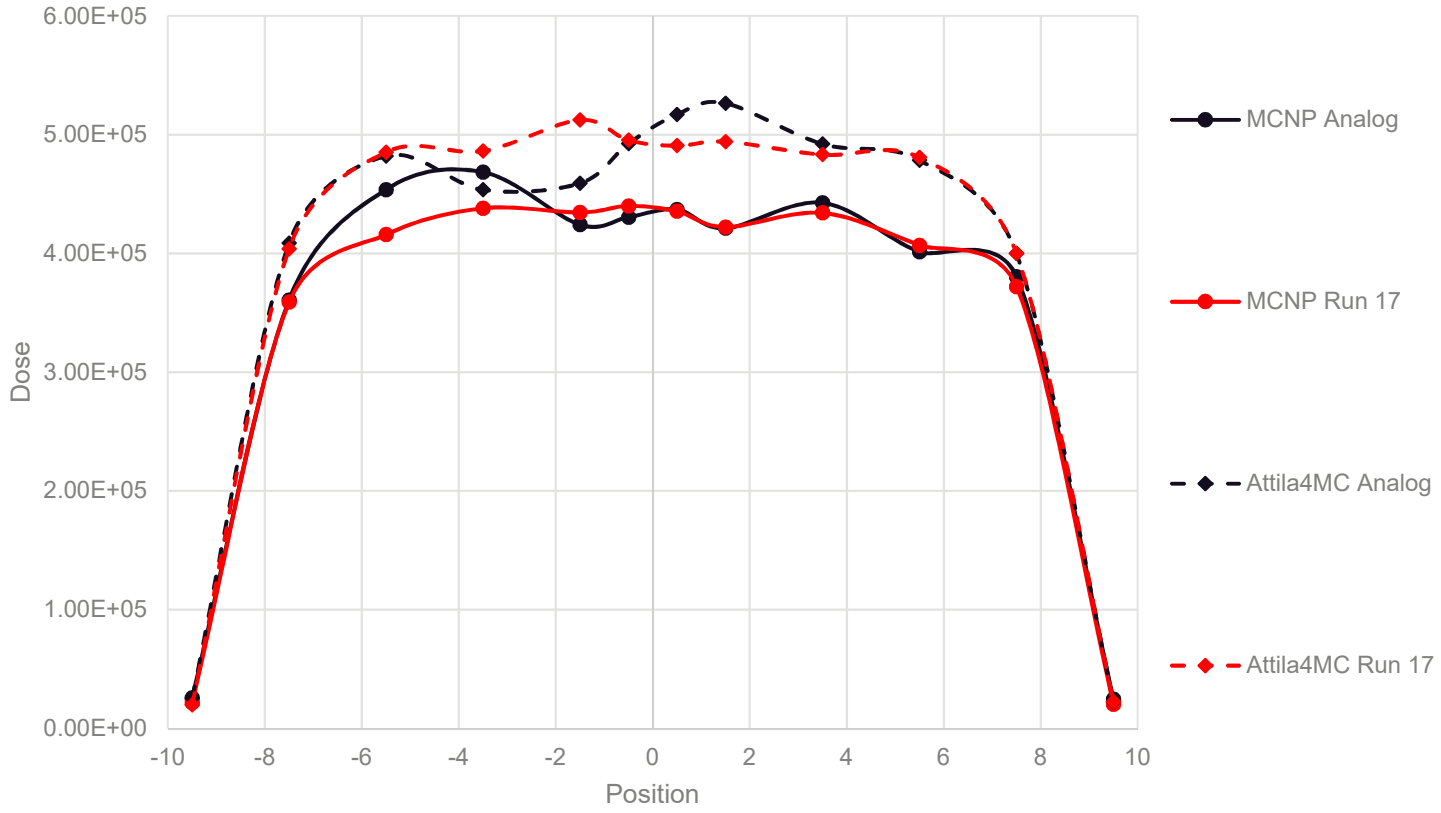
Accelerator Design in SpaceClaim



Attila4MC Meshing

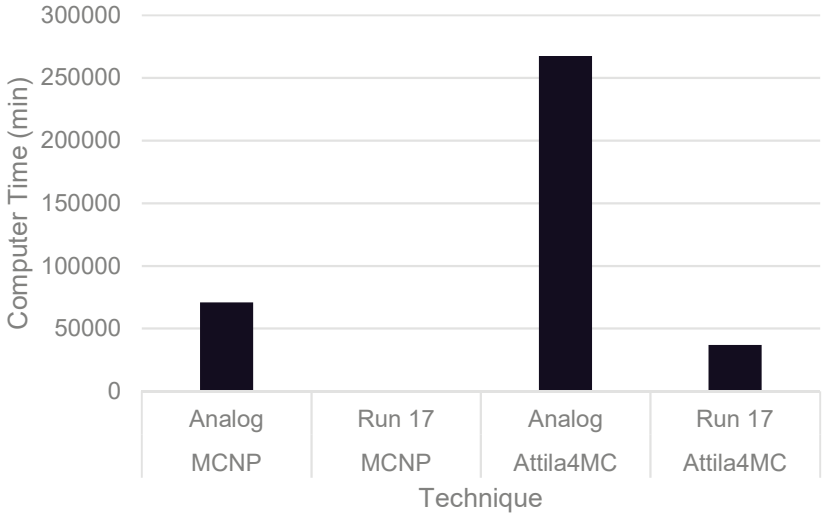


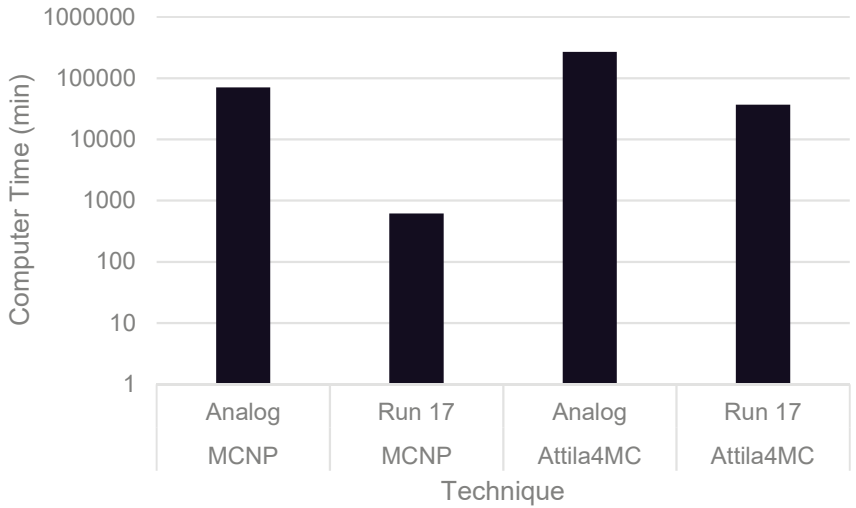
Attila4MC Results



Attila4MC Efficiency

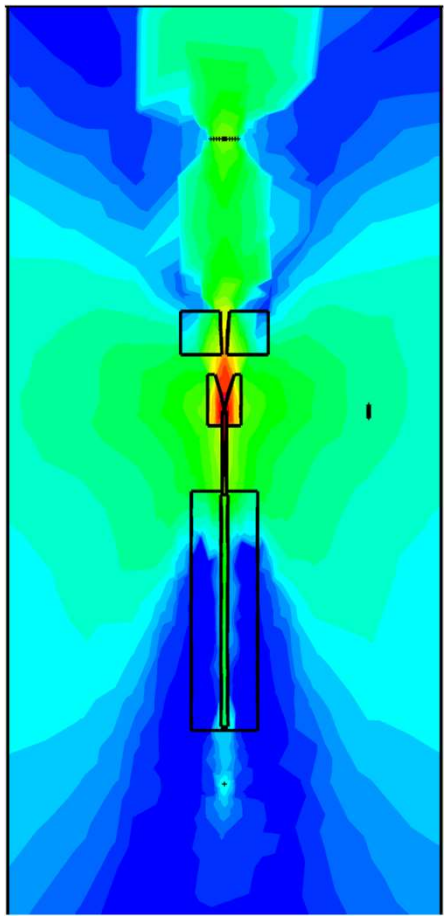
This time is NOT a 1:1 comparison

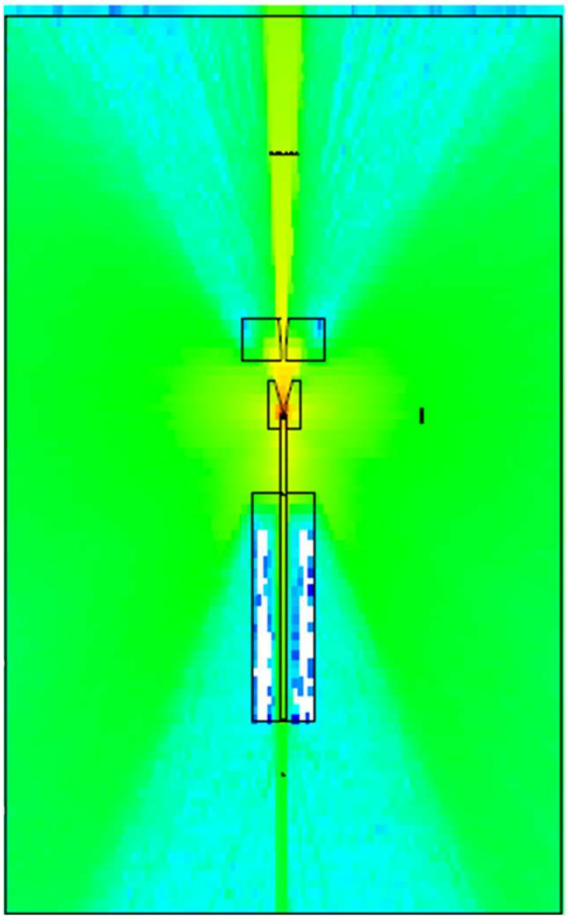




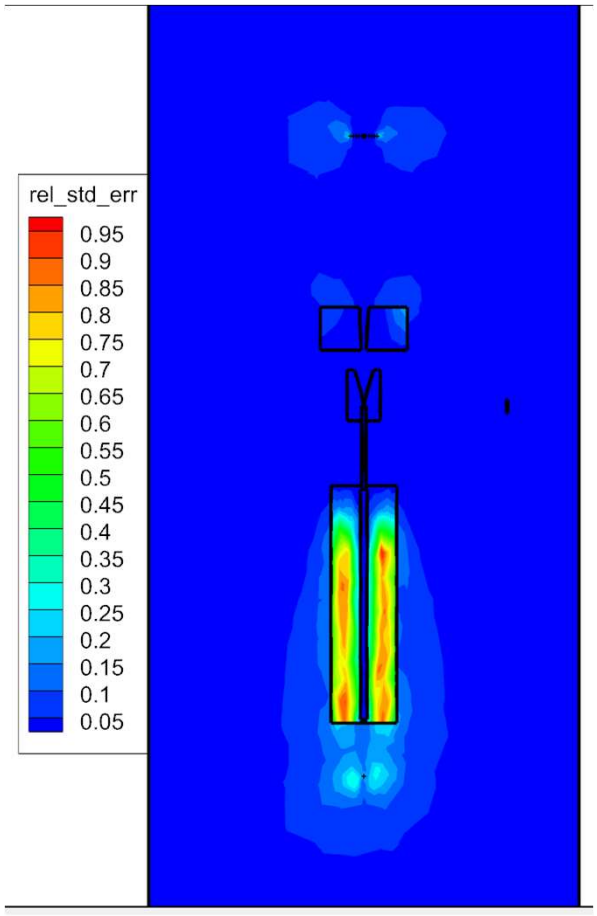
Run:	Technique:	Computer Time (min)	Leakage		Side		Beam	
			Dose	Relative Error	Dose	Relative Error	Dose	Relative Error
MCNP	Analog	70700.47	13695	0.0219	25734	0.1849	430540	0.0463
MCNP	Run 17	616.08	13015	0.0098	21603	0.0878	439960	0.0212
Attila4MC	Analog	267421.4	13430	0.0219	25404	0.1882	492484	0.0428
Attila4MC	Run 17	36679.1	13625	0.0098	19887	0.0920	495269	0.0199

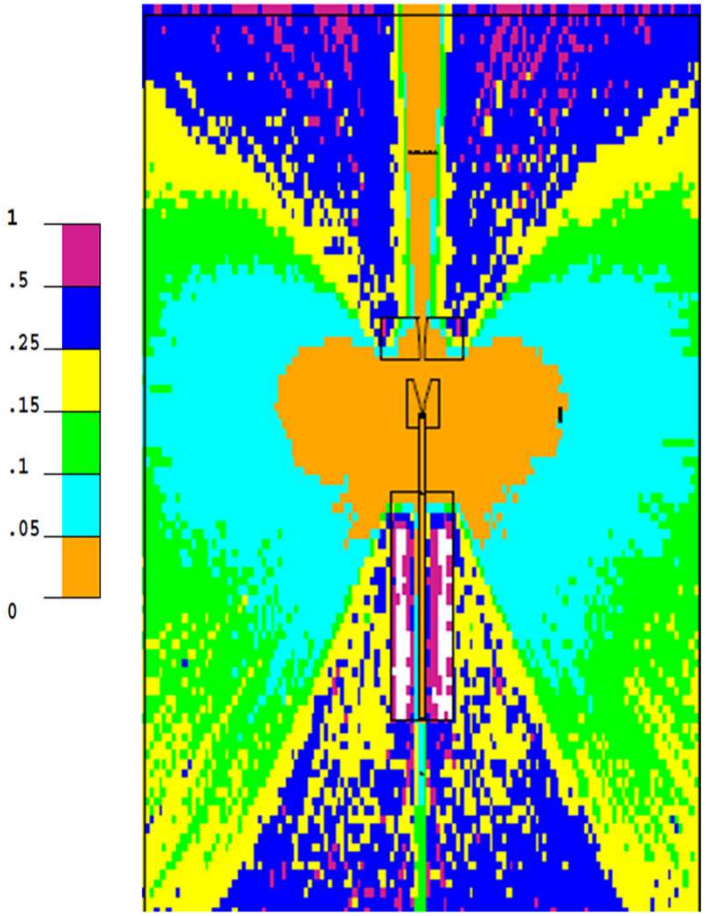
Attila4MC Dose Visualization



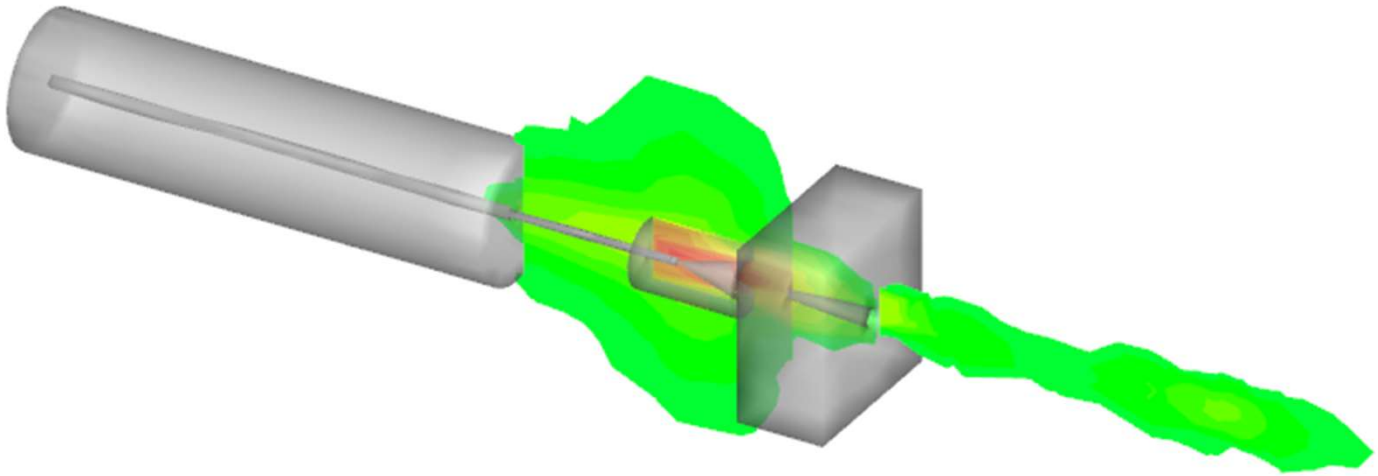


Attila4MC Relative Error

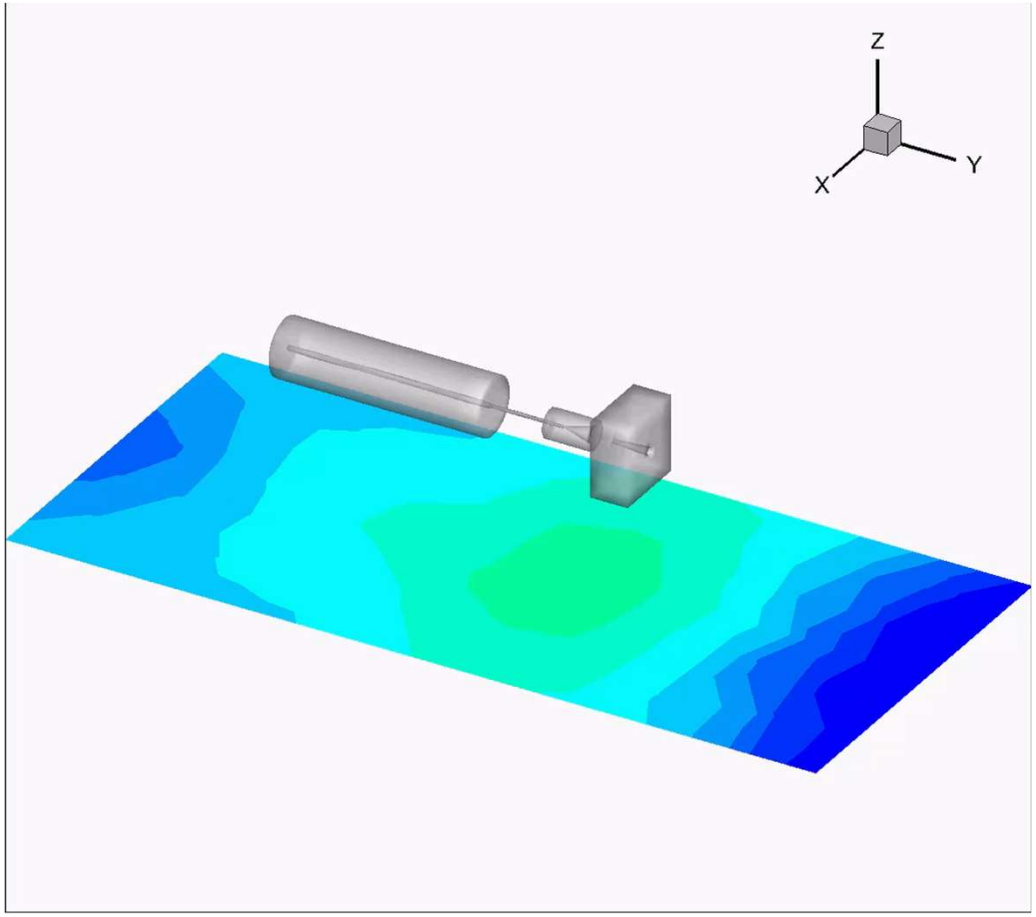




Attila4MC Visualizations



Attila4MC Visualizations



Conclusion - Results

- The electron beam striking the target is computationally intensive
  - Highly accurate target modelling likely to be very important
- Variance Reduction Techniques are very important for Accelerators
  - Bremsstrahlung biasing enables much better sampling
  - Electron cut reduce time required to achieve results
  - Disabling knock-on electrons also achieves reduced time
- Partially Deterministic Techniques achieve results in low-scoring areas

Conclusion – Further Development

- Future Project: Master's Degree
  - Modelling CSU Trilogy and its vault
  - Comparison between Attila4MC, MCNP, Measurements
  - Variance Reduction for Shielding

Questions?